Marco Polo: near Earth object sample return mission

Journal Item

How to cite:

Dotto, E.; Barucci, M. A.; Yoshikawa, M.; Koschny, D.; Boehnhardt, H.; Brucato, J. R.; Coradini, M.; Franchi, I. A.; Green, S. F.; Josset, J. L.; Kawaguchi, J.; Michel, P.; Muinonen, K.; Oberst, J.; Yano, H. and Binzel, R. P. (2008). Marco Polo: near Earth object sample return mission. Memorie della Società Astronomica Italiana - Supplementi, 12(Supple) pp. 102–109.

Mem. S.A.It. Suppl. Vol. 12, 102
© SAIt 2008

Memorie della
Supplementi

Marco Polo: Near Earth Object sample return mission

E. Dotto[1], M.A. Barucci[2], M. Yoshikawa[3], D. Koschny[4], H. Boehnhardt[5], J.R. Brucato[6], M. Coradini[7], I.A. Franchi[8], S.F. Green[8], J.L. Josset[9], J. Kawaguchi[3], P. Michel[10], K. Muinonen[11], J. Oberst[12], H. Yano[3], and R.P. Binzel[13]

[1] INAF-Osservatorio Astronomico di Roma (I)
e-mail: `dotto@mporzio.astro.it`
[2] LESIA- Paris Observatory (F)
[3] JSPEC/ JAXA (J)
[4] ESTEC /ESA (NL)
[5] MPI Lindau (D)
[6] INAF-OAA, Florence (I)
[7] ESA HQ, Paris (F)
[8] The Open University (UK)
[9] SEI, Neuchatel (CH)
[10] Univ. Nice, Obs. de la Côte d'Azur (F)
[11] Univ. Helsinki Observatory (FIN)
[12] DLR Berlin (D)
[13] MIT, USA

Abstract. Marco Polo is a joint European-Japanese mission of sample return from a Near Earth Object. The Marco Polo proposal was submitted to ESA on July 2007 in the framework of the Cosmic Vision 2015-2025 context, and on October 2007 passed the first evaluation process. The primary objectives of this mission is to visit a primitive NEO, belonging to a class that cannot be related to known meteorite types, to characterize it at multiple scales, and to bring samples back to Earth.

Marco Polo will give us the first opportunity for detailed laboratory study of the most primitive materials that formed the planets. This will allow us to improve our knowledge on the processes which governed the origin and early evolution of the Solar System, and possibly of the life on Earth.

Key words. Near Earth Objects – Sample Return – Space Mission

1. Introduction

The Near–Earth Object (NEO) population comprises both asteroids and comet nuclei on orbits with perihelion distances q≤1.3 AU, which periodically approach or intersect the Earth's orbit. They are one of the most interesting populations of small bodies in the Solar System, considering also that they constitute

---

Send offprint requests to: E. Dotto

a potential hazard for the Earth. Due to the short dynamical lifetimes of their orbits, NEOs must be continuously replenished from major small bodies reservoirs, identified mainly in the asteroid main belt, with a possibly significant contribution of extinct cometary nuclei. NEOs are therefore representative of asteroids and comets which are the remnants of the primitive leftover building blocks (planetesimals) of the Solar System formation processes.

More than 5300 NEOs are currently known, but the whole population seems to contain 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). Our knowledge of the structure and composition of NEOs is still rather limited, since only ∼10% of the known NEOs have spectral types determined from observations. The most important characteristic is the high degree of diversity in terms of physical propertiers. Some objects have very elongated shapes, others have complex, non-principal axis rotation states, very long and very short rotational periods are observed, and also binary systems are known. NEO diversity is also emphasized by the different taxonomic types found within the population: all the taxonomic classes present among main belt asteroids are recognized among NEOs. The taxonomic classification of NEOs can give some hints about the regions of the Solar System where these objects come from: E-types seem to come from the inner asteroid belt, S- and Q-types seem to come from the same main-belt region, C-types could come from the mid to outer belt, while P-types come from the outer belt, and D-types seem to be related to the Jupiter family comets. The knowledge of the chemical and mineralogical composition of NEO surfaces gives us an insight into the processes that governed the formation and evolution of our planetary system, and of the material which formed the protoplanetary nebula at different solar distances. Moreover, it can provide information on the evolution of small bodies in the interplanetary regions (Ciesla and Charnley, 2006).

The study of the physical nature of NEOs is very interesting also in view of the potential hazard posed to our planet. NEOs are responsible for most meteorite falls and of the occurrence of occasional major catastrophic impact events. Therefore, their physical characterization is essential to define successful mitigation strategies in the case of possible impactors. In fact, 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.

NEOs play an important role also in exobiological scenarios: in fact the delivery of exogeneous material from primitive NEOs is invoked by current theories for the triggering of life on Earth (Chyba et al. 1994). It is well known that the planets of the inner Solar System experienced an intense influx of cometary and asteroidal material for several hundred million years after they formed. The earliest evidence for life on Earth coincides with the decline of this enhanced bombardment. The fact that the influx contained vast amounts of complex organic material offers a possibility that it may be related to the origin of life on the Earth.

On the basis of all these considerations the NEO population is an important target both for ground based and space investigation. Two space missions have already been devoted to the study of NEOs: the NASA mission NEAR Shoemaker which during 2001 performed a complete investigation of 433 Eros, and the Japanese mission Hayabusa that reached 25143 Itokawa, in 2005.

At a European level, ESA proposed in 2007 a preparation initiative for a sample return space mission to a NEO, inserting direct laboratory analysis of NEO samples among the major topics to be investigated in the Cosmic Vision 2015-2025 timeframe. In this context, the joint European-Japanese proposal of the Marco Polo space mission passed the latest evaluation process in October 2007.

2. The Marco Polo mission concept

The primary objective of Marco Polo is to reach a primitive NEO, to globally characterize its physical properties, to collect a sample and to bring it back to the Earth.

Marco Polo will give the first opportunity to perform detailed laboratory analysis of unaltered extra-terrestrial material.

The mission will enable us to:

- determine the physical and chemical properties of the target body, which are representative of the planetesimals present in the early solar nebula;
- identify the major events (e.g. agglomeration, heating, aqueous alteration, solar wind interactions, ...) which influenced the history of the target;
- determine the elemental and mineralogical properties of the target body and the geological context of the surface;
- search for pre-solar material yet unknown in meteoritic samples;
- investigate the nature and origin of organic compounds on the target body;
- identify organic compounds which may reveal the origin of pre-biotic molecules;
- understand the role of minor body impacts in the origin and evolution of life on Earth.

2.1. Scientific objectives

A mission to a NEO, and laboratory experiments on the collected sample will give us useful information to give an answer to several still open questions.

What were the processes occurring in the primitive Solar System and accompanying planet formation?

As mentioned above, NEOs are widely believed to be representative of asteroids and comets. Since asteroids and comets are presumed to be the remnants of the planetesimals that formed planets and satellites, the analysis of NEOs can offer the unique opportunity to investigate the nature and structure of the material in the protoplanetary disk. Elemental and isotopic analysis of unaltered material from a primitive C- P- or D-type NEO should help us to investigate the physical and thermal processes which governed the early phase of planetary formation and to have some constraint on their timing.

Do NEOs of primitive classes contain presolar material yet unknown in meteoritic samples?

It is widely accepted that carbonaceous chondrite meteorites contain the most pristine material still available in the Solar System. Primitive NEOs show evident spectral similarities with these meteorites. Therefore, it is reasonably expected that a sample taken from the surface of a primitive NEO could contain abundant presolar grains, particularly silicates, and pristine materials less robust than those on meteorites that must have survived the meteorite formation processes.

What is the link between the vast array of spectral information on asteroids and the detailed knowledge available from meteorites? How did asteroid and meteorite classes form and acquire their present properties? How do asteroids and meteoritic classes relate to each other? What processes can be identified as happening on the surface of these small airless bodies as a result of exposure to the space environment and collisions?

Meteoritic analogues have been assessed for several taxonomic classes of asteroids (Gaffey et al. 1993), and some asteroids have been suggested to be the parent bodies of some meteorites delivered on the Earth (Migliorini et al. 1997a,b; Morbidelli et al. 2006). Nevertheless the link between NEOs and meteorites is still far from well understood. A significantly greater mineralogical diversity is evident among asteroids than meteorites. This seems to suggest that the delivery of meteorites is due to a few events, possibly drawn by some selection effects, such as the dynamical characteristics of the parent body and/or its structure and nature. As an example, it is evident that only the strongest material can survive atmospheric entry, but it is not known whether this material is representative of the dominant material in space (Chyba et al. 1994). Considering that space weathering effects alter the physical and spectral properties of the material on the surface of atmosphereless bodies, the comparison among reflectance spectra of meteorites and NEOs can return only poor or ambiguous results. A space mission able to bring back a sample and to characterize the sampling site, offers the unique opportunity to perform detailed mineral chemistry and isotopic measurements. The comparison among telescope spectra of the visited primitive NEO and laboratory reflectance spectra of individual components from the returned sample will give us the ground truth needed for the interpretation of all the data from remote observations.

What are the main characteristics of the internal structure of a NEO both physically and chemically? What are the elemental and mineralogical properties of the asteroid samples and how do they vary with geological context on the surface? How did major events (e.g. agglomeration, heating, aqueous alteration) influence the history of planetesimals?
The global characterization of the target performed by Marco Polo during the orbiting (or hovering) phase, combined with laboratory analysis of the material sampled by the surface, can give insight into the internal structure of the visited NEO. The study of its shape, volume and gravitational field will give us important hints on its density and nature. These data combined with laboratory results will allow us to derive important indications on the mineralogy, composition, chronology and history of the visited NEO.

What is the nature and origin of organic compounds on a NEO? How do NEO organics shed light on the origin of molecules necessary for life? What is the role of NEO impacts in the origin of life on Earth?
It is widely believed that C- P- and D-type asteroids are primitive bodies whose surfaces contain organic materials. Nevertheless, evidence exists that primitive objects belonging to different taxonomic classes experienced a quite different thermal and physical evolution. Barucci et al. (1998) found that about 60% of the C-type asteroids located betwewn 2.5 and 3.5 AU from the Sun experienced aqueous alteration processes, namely liquid water was present on their surface in some epoch. The analysis of the D-type surfaces, mainly composed of anhydrous minerals and organic matter, suggests instead that these objects never experienced any significant aqueous activity.
The present knowledge of the most primitive oganic materials is mainly due to the analysis of the Stardust cometary samples and of IDPs. The analysis in terrestrial laboratories of an unaltered sample from a primitive NEO will allow us to eliminate the terrestrial contamination present in meteorites, and therefore to have some definitive information on the processes which governed the formation of carbonaceous matter in interplanetary material, including key biological compounds like the amino acids.

Why are the existing meteorite specimens not suitable? Why do we need to return a sample to Earth?
As mentioned above the available meteoritic samples are obviously altered by atmospheric entry. All of them have survived the meteorite formation processes that have probably modified their pristine material. IDPs, micron-sized fluffy dust grains, display mineralogical, chemical and isotopic signatures, not found in meteorites, that strongly indicate formation and/or residence in the ISM or solar accretion disk. Such primitive material must have been stored somewhere, perhaps in primitive asteroids or in comets. As an example the Tagish Lake meteorite, significantly more friable than other carbonaceous chondrites, appears particularly primitive and perhaps related to the primitive D-type asteroids (Hiroi et al. 2006).

A sample return space mission to a primitive NEO will allow us to directly analyse unaltered material less robust than the tough, coherent rocks available in meteorite collections. A detailed microscopic study with very high levels of analytical precision of the material collected at the surface or sub-surface of the target can only be achieved in terrestrial laboratories. A sample return mission will allow us to perform detailed laboratory experiments that cannot yet be performed by ”in situ” laboratories. The mineralogical, chemical and isotopic analyses of grains, the actual organic analyses and the investigation of the chronology of the sample will require high precision and multiapproach measurements only available in terrestrial laboratories. Obviously, the analysis of samples, returned to Earth and stored on ground, will benefit from future development in analytical techniques. A sample return mission can therefore provide significant scientific results far beyond the actual mission duration.

3. Target selection

NEOs are much more accessible for space missions than the other populations of small bodies of the Solar System. The accessibility from Earth of a potential target of a space mission is studied by Hohmann transfer formulation which gives the minimum energy transfer trajectory between two orbits in space, in terms of the velocity changing (delta–V) needed to realize a rendez-vous mission (e.g. orbiting around an object). Starting from the classical definition of "accessibility" of a celestial body, Fig. 1 shows that NEOs can be more accessible than the Moon or as difficult to reach as Jupiter and beyond.

About 15 possible targets of high scientific interest have been selected covering a wide range of launch windows in the time span 2017-2019, with mission duration from about 4 to 8.5 years. Among them there are the dormant comet 4015 Wilson-Harrington, which can provide insights into the origin and evolution of comets transported into near-Earth space as well as the unknown link between asteroids and comets, and several primitive NEOs, offering excellent samples of less thermally evolved material in the solar nebula. The target selection is at present a still ongoing process. The current number of easily accessible objects will certainly increase in the coming years, and observational campaigns dedicated to newly discovered objects will be organized in order to characterize among them the scientifically interesting targets for this sample return mission to a primitive NEO.

4. Mission scenario

Several mission scenarios have so far been considered depending on the selected suitable target. For all of the studied scenarios a Soyuz-Fregat launcher is needed.

The baseline mission scenario includes a Mother Spacecraft (hereafter MSC, which will benefit from the European experience on spacecraft, and the Japanese Hayabusa spacecraft), sampling devices, a re-entry capsule and scientific payload.

After an initial heliocentric orbit for an Electric Delta-V Earth Gravity Assist (EDVEGA), the MSC starts its interplanetary cruise phase toward the target, rendezvous with the target, and orbits (or hovers above) the target to perform its global characterization with onboard remote sensing scientific instruments. This global characterization is needed to determine the shape of the target and its gravitational field, to study the surface morphology and therefore to select the landing and sampling sites. During the descent sequence, two small rovers (of about 10 cm) could be released in order to perform some characterization of the surface in different places than the sampling site. These two small hoppers profit from the heritage of the JAXA hopper MINERVA carried by the Hayabusa mission.

The possibility to carry a Lander (profiting from the Rosetta Lander Philae heritage) has also been studied. It would perform a soft landing, anchor to the asteroid surface, and would carry out in situ measurements of the surface/ subsurface material near the sampling site, within several Earth days.

The mission will be optimised for multiple sampling attempts at multiple sites, potentially utilising different sampling devices. Drawing on expertise from Haybusa (JAXA) and Rosetta (ESA) missions - this will permit optimum sample collection from a wide range of surface properties. All the sampling devices will be mounted on a retractable extension arm. After the sampling and ascent of the MSC, the arm is retracted to transfer the sample containers into the MSC. Once the sample containers are inside the MSC, they are pushed into the sealing system and then into the Earth re-entry capsule.

The MSC returns towards the Earth and releases the capsule for the high-speed re-entry into Earth's atmosphere. The capsule will be retrieved on the ground at a low to mid latitude, uninhabited area.

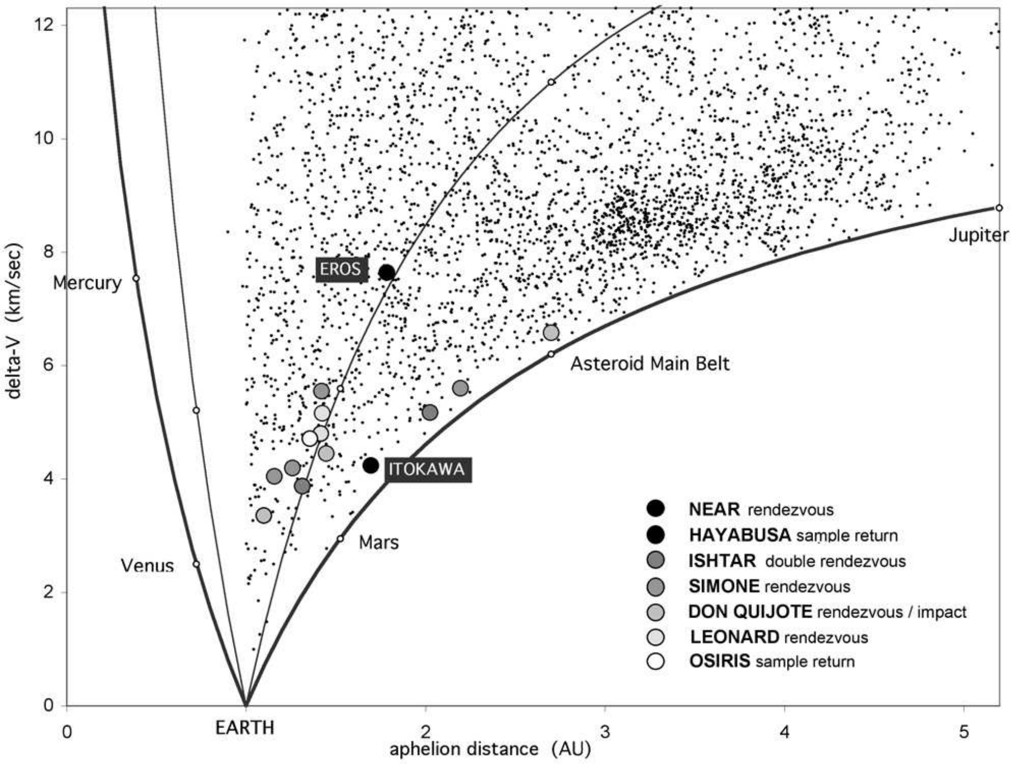

Fig. 1. The accessibility of NEOs versus required delta-V (adapted from Perozzi et al. 2001).

After appropriate space quarantine and sterilization processes, samples will be taken out of the capsule in a dedicated curation facility to conduct initial sample characterization, prior to their distribution to designated scientists for detailed analyses.

The acquired scientific data and the results of the analyses on the returned samples will be jointly archived in Europe and Japan for public release after the proprietary period.

The ground segment can be classical including a flight dynamics operation centre, using a very representative simulator with an important NEO environment modelling component.

5. Payload concept

In order to reach the above mentioned scientific objectives a multi-scale approach is proposed. The MSC will perform a macroscopic global scale analysis (from m to km), the lander, if present, will reach the local scale (from mm to cm), while the microscopic scale (from nm to μm) will be reached by laboratory analyses of the returned samples.

The key measurements that will be performed on the target are:

Global-scale:

- Overall characteristics: orbit, rotation, size, shape, mass, gravity and density
- Surface topography and morphology (boulders, craters, fractures)
- Main characteristics of the internal structure

- Mineralogical and chemical compositions
- Dust conditions around the object

Local-scale:
- Mineralogical composition and crystal structure of surface minerals
- Out-gassing volatiles (e.g. H_2O, CO_2, etc)
- Complex organic molecules
- Surface thermal properties

Micro-scale:
- Mineralogy and mineral chemistry
- Isotope chronology of formation events
- Organic and volatile inventory and isotopic signatures
- Spectroscopic characterisation

The MSC will be equipped with instruments that will operate during the approach, orbiting (or hovering) and descent phases, and will be essential for landing site selection, sample context characterization and spacecraft safety. Moreover, remote measurements performed with payload instruments on board the MSC will perform the global characterization of the target (e.g.: size, shape, mass, internal structure, etc.). The obtained information will allow us to properly link the collected samples with the physical properties of the parent body. The MSC scientific payload includes a high resolution imaging system, spectrometers covering visible, near-infrared and mid-infrared wavelengths, a laser altimeter, a radio science experiment and a neutral particle analyser. Other instruments, in secondary priority, can be added during the assessment phase study, such as radar, X-ray spectrometer, solar monitor, γ-ray spectrometer, and neutron counter.

The Lander, if present, will perform in situ measurements to characterize location, context, and surface environment of the collected sample. The scientific payload on the Lander could include close-up/panoramic camera, electron microscope, X-ray diffractometer, volatile detector, microbalance, mass spectrometer, and thermal sensors. Other instruments, such as mid-infrared spectrometer, Raman microscope, γ-ray spectrometer, alpha particle X-ray spectrometer, surface package, electric field sensor can also be added.

A more elaborate payload should be defined after detailed study, depending on the chosen mission option and target.

The sampling manoeuvres will be performed using a combination of the navigation camera, LIDAR, laser range finders, fan beam sensors, target makers, and touchdown sensors.

6. Conclusion

NEOs are representative of the less evolved populations of small bodies of the Solar System (asteroids and comets), but have the advantage to be more accessible for space missions. A space mission to a primitive NEO provides major opportunities to have some hints on the origin and early evolution of the Solar System through the investigation of the primordial cosmochemistry of the solar protoplanetary disk, and the investigation of the origin and properties of the planetary building blocks.

The Marco Polo mission has the potential to revolutionize our knowledge of primitive materials, essential to understand the conditions for planetary formation and emergence of life, and can provide important information to develop strategies to protect the Earth from potential hazards.

Moreover, a robotic sample return mission to a NEO, besides its scientific relevance, is innovative and:

i) will allow us to test new challenging technologies (e.g. robotic sampling from MSC, re-entry capsule, communication);
ii) will allow us to develop new microanalysis techniques and to prepare laboratory facilities for next generation analysis of extraterrestrial samples;
iii) will be the precursor of future sample return missions to high surface gravity bodies (e.g. Mars).

References

Barucci, M.A., Doressoundiram A., Fulchignoni M., et al. 1998, Icarus, 132, 388

Chyba C.F., Owen T.C., Ip W.-H. 1994, in Hazards due to comets and asteroids (Gehrels T. ed), University of Arizona Press, Tucson, 9

Ciesla F.J., Charnley S.B. 2006, in Meteorites and the Early Solar System II (Lauretta D.S. and McSween H.Y. eds), University of Arizona Press, Tucson, 209.

Gaffey M.J., Burbine T.H., Binzel R.P. 1993, Meteoritics 28, 161

Hiroi T., Zolensky M.E., Pieters C.M. 2006, Science 293, 2234

Migliorini F., Manara A., Cellino A., et al. 1997a A&A, 321, 652

Migliorini F., Scaltriti F., Farinella P., et al. 1997b, Icarus, 128, 104

Morbidelli A., Jedicke R., Bottke W.F., et al. 2002, Icarus, 158, 329

Morbidelli A., Gounelle M., Levison H., Bottke W. 2006, Met. and Plan. Scie., 41, 875

Perozzi E., Rossi, A., Valsecchi, G.B. 2001, Planet and Spa. Sci., 49, 3

Stuart J.S., Binzel R.P. 2004, Icarus, 170, 295