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Sample Return Missions from Minor Bodies: Achievements, Future Plan and Observational Support

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Abstract We are entering in a new era of space exploration signed by sample return missions. Since the Apollo and Luna Program, the study of extraterrestrial samples in laboratory is gathering an increased interest of the scientific community so that nowadays exploration program of the Solar System is characterized by swelling sample return missions. Beside lunar samples, the NASA Stardust mission was the first successful space mission that on 15 January 2006 brought to Earth solid extraterrestrial samples collected from comet 81P/Wild 2 coma. Grains were collected during cometary fly-by into aerogel and once on Earth have been extracted for laboratory analyses. In the coming two decades many space missions on going or under study will harvest samples from minor bodies. Measurements required for detailed analysis that cannot be performed from a robotic spacecraft, will be carried out on Earth laboratories with the highest analytical accuracy attainable so far. An intriguing objective for the next sample return missions is to understand the nature of organic compounds. Organic compounds found in Stardust grains even if processed to large extend during aerogel capturing are here reported. Major objectives of Marco Polo mission are reported. Various ground-based observational programs within the framework of general characterizations of families and classes, cometary–asteroid transition objects and NEOs with cometary albedo are discussed and linked to sample return mission.

Keywords Laboratory · Dust · Space mission · Astroids · Comets · Spectroscopy

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1 Introduction

Until January 2006, before Stardust/NASA capsule with sample returned from comet 81P/Wild 2, cometary grains are the only extraterrestrial samples, from a specific astronomical body other than the Moon, available for direct analyses. Other important extraterrestrial samples of uncertain parent body available for laboratory studies were meteorites, Interplanetary Dust Particles (IDPs) collected from the stratosphere with high-altitude aircrafts (Brownlee 1994) and by balloon-borne instruments (Palumbo et al. 2008). Sources for IDPs are comets and asteroids (Brownlee 1994), the most pristine bodies in the Solar System. Hence, such objects can be considered as reservoir of fossil pre-solar dust that provides a unique access to the materials and processes occurred during Solar System formation and early evolution. During the past years, a very large number of IDPs have been collected and analyzed. Their properties have been accurately determined, showing a wide range of compositions and morphologies (Rietmeijer 1998). Typical IDPs are fine-grained mixtures of minerals and amorphous components. Particles may contain sulfides, olivine, pyroxene, Ca–Al rich inclusions, Fe–Ni metal grains, carbonate and phosphate. Chondritic particles can be anhydrous, composed of olivine and pyroxene silicates, or hydrated, with a mineralogy typical of layer lattice silicates. Some IDPs contain abundant carbonaceous material (over 10 wt%) and GEMS (Glass with Embedded Metal and Sulfides) (Bradley 1994). Single mineral grains are mainly enstatite and have crystallographic structures compatible with formation by direct gas-to-solid condensation (Bradley et al. 1983), consistently with observations of dust in circumstellar environments and comets (Wooden et al. 2000). Analysis of IDPs is complicated by the alteration effects experienced by IDPs as they travel through Earth's atmosphere (Genge and Grady 1999). Recently, the possibility of collecting IDPs in space has been explored using low density material as collector; the advantage of this collection technique is that the samples are not altered by atmospheric entry effects (Borg and Maag 2004). At present, results on IDPs collected in circumterrestrial environment have been promising (Horz et al. 2000, Burchell et al. 2001) and the development of more and more powerful techniques is under progress.

Despite the information already acquired, a number of issues remain unsolved:

– due to selective effects (e.g., Earth capture, atmospheric-entry survival and collection techniques) the set of collected samples is only partially representative of the complex extraterrestrial dust population;
– the discrimination criteria between cometary and asteroidal IDPs are still not well defined;
– the links between IDPs, asteroids, comets, interstellar and circumstellar dust are still not fully understood.

Sample return missions will open a new age in the study of solar system by means of analysis of extraterrestrial materials of well-known origin. Sample return missions will bring back on Earth samples from targets widely characterized and studied with geological contexts that are never known for meteorites and IDPs. To better design a sample return mission is fundamental to carry out photometric and spectroscopic observations of the target. The ground or space observations will allow to maximize the scientific return for space mission, providing tools to define the nature of target.

2 Achievements: Stardust Mission

NASA Stardust mission was a successful space mission that on 15 January 2006 brought to Earth solid extraterrestrial samples collected from the comet 81P/Wild 2 tail. Cometary grains, thousands of micron and submicron-sized dust particles, were collected during cometary fly-by into aerogel and once on Earth extracted for laboratory analyses. Collection of interstellar dust was planned as an additional objective of the Stardust mission. The particles collected by Stardust should be the same materials that accreted along with ices to form the comet, about 4.57 billion years ago, when the Sun and planets formed. Comet 81P/Wild 2 particles resulted to be extremely heterogeneous in composition and form, representing a virtual sampling of every part of the protosolar nebula (Zolensky et al. 2006). The analyses showed a lack of reaction among adjacent mineral grains suggesting that these materials were subjected to very little additional processing after they were accumulated into the cometary parent body. Thus, 81P/Wild2 particles are repositories of primitive protosolar materials, including presolar circumstellar and interstellar materials. The majority of the large crystalline silicates collected by Stardust have solar isotopic compositions, different from what is seen in interstellar grains (McKeegan et al. 2006). Wild 2 samples contain pre-solar materials, but they clearly are not just a collection of submicron interstellar grains.

Laboratory analyses of collected samples are used not only to better understand initial formation stages and further evolution of the Solar System and in particular of minor bodies, but also to understand the nature, the history and the distribution of the organic compounds in the Solar System. Organic molecules in comets show a higher complexity than in the diffuse ISM due to the reaction of fine grains of variable compositions such as silicates, oxides or sulfides with various icy molecules. These processes were monitored by infrared spectroscopy astronomical observations and analyses on extraterrestrial materials, in particular by a careful survey of the 3.4 mm region. The CH_2/CH_3 IR band ratio was measured as 5.9 and 3.7 for the 81P/Wild 2 (Rotundi et al. 2008) and IDPs particles (Matrajt et al. 2005) respectively. These values are significantly larger than 2.2 observed in diffuse ISM (Pendleton et al. 1994). Furthermore, IR spectral evidence indicates the organics in the diffuse ISM contain relatively little oxygen (Pendleton and Allamandola 2002, Dartois et al. 2005). High O contents and the high CH_2/CH_3 IR band ratio with respect to what is measured in the diffuse ISM, suggest that cometary organics are not the direct result of stellar ejecta or diffuse ISM processes but rather result from dense cloud and/or protosolar nebular processes (Sandford et al. 2006).

In this respect, Raman analysis is very sensitive to the chemical composition and structure of different carbonaceous materials (diamond, graphite, glassy carbon, hydrogenated amorphous carbon, etc.). Extraterrestrial dust grains are usually analyzed by Raman spectroscopy to infer information on the composition and processing suffered before and after they left their parent bodies. Parameters taken from Raman spectra of IDPs have been plotted and compared with the same parameters from Raman spectra of cosmic dust analogs obtained in laboratory by arc discharge or by ion irradiation of carbon-containing frozen gases, graphite and diamond (Baratta et al. 2004; Brunetto et al. 2004; 2009, Ferini et al. 2004). Such a comparison could allow to propose a possible mechanism able to induce an “evolution” of IDPs. In particular, amorphous carbon with different degrees of order could be indicative of different irradiation doses by solar wind particles and fast solar protons suffered by IDPs in the interplanetary medium before collection. It is interesting to compare the properties of the amorphous carbon phase of Stardust cometary grains with that of ion irradiated ices. In fact, according to Strazzulla and Johnson (1991), the superficial layers of comets (0.1–0.5 m) are exposed to an irradiation dose of up to 600 eV/molecule. This energetic processing drives the formation of a substantial "crust" of non-volatile material, left over when volatile material from the deeper layers sublimates in the passages near the Sun.

In almost all Raman analyses on IDPs, the only features seen are the amorphous carbon "G" and "D" bands superimposed upon a fluorescence background of variable intensity, although features due to minerals have been detected in a few cases (e.g., Rotundi et al. 2007). The rarity of detections of minerals in Raman spectra could be due to some combination of: (a) fluorescence that masks weak features; (b) the opaque nature of the samples that prevents deep visible laser penetration; and (c) the very high Raman scattering efficiency of the amorphous carbon bands G and D with respect to minerals (Quirico et al. 2005). In case of minerals detection Raman spectroscopy gives the opportunity to separate different silicates (e.g., olivine, pyroxene) and among them to recognize the amount of Fe, Mg and Ca in crystals (that is fayalite versus forsterite, enstatite versus ferrosilite, diopside versus hedembergite, etc.). Raman parameters determined for 81P/Wild 2 particles span a similar range to that observed in IDPs and the most primitive meteorites (Rotundi et al. 2008). They also indicate a strong contamination due to the slowing-down of the incident grains in the aerogel. The compressed or melted aerogel present in the grains is a brake to an easy interpretation of the results of the various analyses performed on the grains.

This considerable amount of critical information, have been retrieved by only <2 years of sample returned analyses. In addition, as for all Sample Return mission, as laboratory instruments will improves over time, the samples will be reanalyzed with improved and new analytical techniques yielding additional results.

3 Future Plan: Sample Return Missions from NEOs

The NEOs are asteroids and comet nuclei in an evolving population with a lifetime limited to a few million years after which most of them end in a Sun-grazing state, or are ejected from the Solar System, while about 10–15% of them collide with a terrestrial planet. Despite the short dynamical lifetime of their orbits, their number is maintained in a steady-state. Most NEOs come from different zones of the main belt, via specific mean motion and secular resonances with Jupiter, with a possibly significant contribution of dormant cometary nuclei. The P- and D-type asteroids are thought to contain water ice at their surface, and they could be bodies of dirty-ice or comet-like rubble piles although we cannot determine this structural property for these asteroids.

The presence of (mostly) water ice that will sublime when close enough to the sun is the signature property of a comet. NEOs, which are no longer on a circular orbit, showing an intermitted coma-like phenomenon are for all practical purposes comets. To strengthen the argument of the real observative link between NEOs and comets, it would be useful to cite the recent work by Fernandez et al. (2005), with a mid-infrared survey of 26 asteroids including 6 NEOs. Using both the comparison of albedos of cometary nuclei and NEOs and the similarity of orbital parameters of the two families, they derived that about 4% of all known NEOs have both comet-like orbits and albedos, and this could represent a quantitative estimate of the fraction of dormant or extinct comets in the present NEOs population. Binzel et al. (2004) point out that the correlation of low albedo D-, C-, and P-types with Jupiter family comet sources reveal a strong source signature for comets within the NEO population. They estimated that 10–18% of the NEO population may be extinct comets. The recent finding of an active comet body in the asteroids belt further eroded the distinction between comets and asteroids. That is to say, there exists a group of primitive objects in the solar system that have all the basic properties of a comet but that remain hidden in the outer asteroid belt until some chance cause allows them to 'turn on,' however briefly. Four missions to active comets, 1P/Halley, 19P/Borelly, 9P/Tempel 1 and 81P/Wild 2, and one still on the way, the ROSETTA mission to comet 67P/Churymov-Gerasimenko, show the incredible scientific yield of such missions but also their limitations expressed in time-commitment.

Most of what we know today about small bodies has been acquired through space missions fly-by of asteroids (951 Gaspra, 243 Ida/Dactyl, 253 Mathilde, 9969 Braille, and 5535 AnneFrank) and of comet (1P/Halley, 19P/Borrelly, 81P/Wild 2, 9P/Tempel 1). Only two missions have been specifically devoted to a rendezvous with a NEO, namely the NASA NEAR Shoemaker and the JAXA Hayabusa missions. A mission to a NEO can be achieved in a shorter time and at relatively low cost. Over 4,500 NEOs were catalogued so far from a steady-state population that includes hundreds of thousands greater than 100 m. Primitive NEOs (C-, T-, P- or D-type) might preserve many pristine organic materials or molecules including those that might have been were necessary for life to arise and evolve.

The Japanese Hayabusa will be the first sample return mission by Japan's space science agency (JAXA). The goal of the mission is to return powdered or chipped samples from the surface of a small S-type near-Earth asteroid, Itokawa. The spacecraft was launched in May 2002 and rendezvoused with the asteroid in 2005, collecting samples that will be returned to Earth in 2010. Hayabusa 2, currently under development at JAXA, will make further step in exploration of NEOs. It will be launched in 2014 visiting and collecting sample from a C-type asteroid. Under the NASA New Frontiers program, OSIRIS is a mission that proposes to collect pristine sample from the NEO 1999 RQ36. Marco Polo is a joint European-Japanese mission study to perform a sample return from a Near-Earth Object (Barucci et al. 2009). On October 2007, this mission project passed the first evaluation process in the framework of the ESA Cosmic Vision Programme. The principal scientific objective of the mission is to return unaltered materials from primitive undifferentiated C-type asteroid 1999 JU3. Marco Polo is based on a launch in the years 2017/2018 and a re-entry on Earth in the years 2022–2024.

The Marco Polo scientific objectives were discussed (Barucci et al. 2009). It has been showed how wide the scientific themes encompassed by sample return mission from a primitive object are. Laboratory analyses of returned samples will contain a wealth of information able to give the answers to the following questions:

- What were the processes occurring in the primitive Solar System and accompanying planet formation?
- Do NEOs of primitive classes contain presolar material yet unknown in meteoritic samples?
- How did asteroid and meteorite classes form and acquire their present properties? How do asteroids and meteoritic classes relate to each other?
- What is the link between the vast array of spectral information on asteroids and the detailed knowledge available from meteorites?
- What are the main characteristics of the internal structure of a NEO—both physically and chemically?
- 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?

Marco-Polo samples will be collected from a surface that has been subjected to wide temperature variations over the course of the asteroid's orbit and exposed to solar wind and cosmic ion fluxes, as well as to meteorite and micrometeorite impacts. Samples with a selection of centimeter-sized or larger pebbles and a large amount of micrometer-sized to millimeter-sized particles will be collected and delivered to Earth. The elemental and mineralogical compositions of the samples, thus, may span a broad range of minerals, plus simple and in some cases complex organic molecules.

Based on bulk chemistry, bulk isotopic compositions, mineralogy, petrology, and proportions of various chondritic components samples will need to be classified according to classical taxonomical meteorite classification. Preliminary analysis will allow evaluating the degree of alteration suffered in some way by geological processes such as aqueous and hydrothermal alteration, thermal metamorphism, particles irradiation and impacts. These measurements will provide the unprecedented evidence of pristine materials rich in organics that have not suffered such high thermal processing due to atmospheric impact during re-entry on Earth as it occurs in some degree for meteorites. The analytical campaign, thus, can be considered as tackling scientific challenges on a number of scales from the whole-rock properties through the different types of materials present even to the individual grain or molecule.

Stardust mission had as major objective to analyse the mineralogy of cometary grains. This result was totally achieved by the choice of aerogel as grains collecting mechanism. However, the high thermal processing that many cometary particles suffered during the aerogel capture seriously affected the organic components. These have been altered and dispersed inside the aerogel, which behaved like a sponge adsorbing organic molecules (Sandford et al. 2006). As showed before, this made the analyses of organic compounds demanding. Samples returned by a carbon rich C-type asteroid collected by mechanism that does not induce any processing would be suitable for organic measurements because samples will be unaffected by collecting mechanism and, then, maintained pristine. Marco Polo sampling mechanism will gently collect sample from the asteroidal surface satisfying this requirement. Understanding the sources and nature of organic molecules and the chemical processes that led to their formation is, thus, the goal of laboratory measurements. To perform a quantitative measurement of carbonaceous compounds dispersed in bulk material it is necessary, however, to extract and separate them from the samples. This requires the use of destructive analyses causing a significant impact on the total mass sample to be returned on Earth. Another important aspect that needs to be taken into account is that about 1/3 of the sample mass will remain stored in a curation facility for next generation of researchers and future improvement of instrumentation at disposal to the laboratories. Finally, multiple analyses needs to be performed by different laboratories in order to acquire the necessary statistical confidence on scientific results. Such considerations lead to the requirement that the minimum sample mass to be returned is about 10 g.

4 Observational Supports

On-ground and (still few) in situ observations gave much reference to the fact that the classical distinction between inactive asteroids and active comets (in terms of dynamical and physical properties) should be reviewed in the framework of a global evolutionary process in the Solar System, the NEOs being one of the possible final fate of Minor Bodies evolving from the outer regions of the System.

As an example, the dust collected by the recent Stardust mission showed that Jupiter-Family (JF) comet 81P/Wild 2 contained many so-called refractory minerals that previously had been considered to be typical for the inner solar system wherein they were accreted into stony asteroids. Spectroscopic analyses of the nucleus of some comets show that they belong to the infrared class D-type bodies and are therefore, as afar as this property is concerned, indistinguishable from D-type asteroids in the outer asteroids belt and also indistinguishable from the carbon-rich aggregate IDPs that show the same spectroscopic signature (Bradley et al. 1983, 1994). As an example, Licandro et al. (2003) report a NIR (0.9–2.3 μm) spectrum of the JF comet 124P/Mrkos, which is featureless, slightly redder than the Sun, and in fact resembles the spectrum of a D-type asteroid. Furthermore, Licandro et al. (2002) were also the first to publish an IR spectrum of a cometary nucleus (the JF comet 28P/Neujmin 1), together with the spectra of 10 Trojans asteroids. Also in this case, a featureless, slightly redder than the Sun spectra was obtained, with a spectral slope very similar to that of D-type asteroid. De Sanctis et al. (2000) published a visible (0.4–0.98 μm) spectrum of the nucleus of comet 82P/Gehrels 3, which has a particular orbit with very low inclination, moderate eccentricity and a very high Tisserand invariant (it is classified as an Encke-type comet). Also its optical spectral slope is consistent with the mean slope of optical spectra of D-type asteroids, as well as with that of Trojans asteroids.

Another important evidence of the superposition of the different dynamical and physical classes in the inner Solar System is given by the recent discoveries in the field of the debris trails.

The discovery of the cometary debris trails (Sykes et al. 1986, Sykes and Walker 1992) of 8 Short Period Comets (SPCs) and of more than 50 "orphan" trails provided new and strong insights into the nature and composition of cometary nuclei. More recently, 22 different SPCs were observed with an associated debris trail (Reach et al. 2007), confirming the IRAS' suggestion that trails are a common phenomenon associated with virtually all SPCs. Dust trails consist of large (mm–cm), dark, low-velocity particles, covering a portion of the cometary orbit both behind as well as ahead of the comet. In general, they have a long, narrow appearance, extending sometimes tens of degrees across the sky, while having a width of only few arcminutes. The debris trails likely represents the main mechanism by which comets emit mass, e.g., most of the mass that comets loose is in refractory particles. This is important not only in the view of the picture of the composition and structure of the comet nuclei, but also in the framework of the contribution of different sources to the circumsolar dust cloud (the Zodiacal Cloud). In this framework, it is interesting to report the recent observation that at least 2 of the IRAS orphan trails cannot be linked to any known comet and have, instead, orbital parameters consistent with those of main-belt asteroids (Nesvorny et al. 2006), likely deriving from very recent collisional breakups of small bodies.

On-ground observations will help to constrain the evolutionary models of minor bodies in the Solar System (especially in the final part of their lifetime) and, more in particular, will give the general framework in which the information gathered during a space mission to a NEO should be interpreted. Coupled with a study of what is called "accessibility" of the targets (the velocity change Δv needed to realize a *rendez-vous* mission in the framework of present/near future technological level), these observations will help in the selection of the most interesting and suitable target for a space mission to a NEO. Moreover, observation will help to design at best the scientific instruments onboard the spacecraft (e.g., sensitivity ranges and limits) and to constrain the spacecraft operations at the targets (e.g., approach manoeuvres, rendez-vous and/or fly-by passages, lander release), and will give the needed scenario in which the data obtained at the target should be calibrated, analyzed and interpreted.

The observational support to be programmed (both on the selected and back-up targets and in a more general framework) should comprise combined programs with the aid of:

(i) *The multicolor visible photometry*—these observation will allow to completely characterize the more general physical properties of the target: nucleus size, shape, rotational properties (by means of visible light curves), phase function (especially at low phase angle), surface colors. Very useful results for the preparation of Rosetta spacecraft approach to asteroid 2867 Steins have been obtained by means of long-term photometric monitoring with small and medium class *on-ground* telescopes (see e.g., Dotto et al. 2009 and references therein), and will be used to properly calibrate and interpret the results obtained after the asteroid *fly-by* performed by the Rosetta spacecraft on 5th September 2008. Moreover, accurate and high resolution surface photometry is needed to detect the presence of possible cometary activity, since an upper limit on the mass loss rate eventually present on the NEOs' surface has been estimated (from a small survey of 11 NEOs) of the order of 0.1 kg/s, 1–2 order of magnitude smaller than the weakly active comets (Luu and Jewitt 1992). High SNR images of the target and of a consistent ($\sim 2°$) part of its orbit will be useful to identify the presence of associated dust trails that could be indicative of the target being a member of the candidate dormant or extinct comet.

(ii) *The polarimetry*—these observations are useful to constrain the surface composition of the target, by means of the investigation of the polarization minimum and of the inversion angle versus the phase angle, strongly indicative of the microstructure and composition of the asteroid surface. The polarization is strictly related to the taxonomic asteroidal class, as extended surveys of asteroidal polarization properties show (Fornasier et al. 2006a). Moreover, the albedo of the target can be derived starting from the polarimetric slope. This approach has been followed e.g., for asteroid 2867 Steins, target of the ESA Rosetta mission, which has revealed a "bright" object with albedo of 0.45 ± 0.10 (Fornasier et al. 2006b).

(iii) *The visible and near-IR spectroscopy*—these observations will allow to study the surface composition of the target, by searching for spectral evidences of minerals and mixtures present on its surface. This approach has been followed e.g., for asteroid 2867 Steins, target of the ESA Rosetta mission, revealing a strong feature at about 0.5 μm, a weaker feature at about 0.96 μm and a flat and featureless behavior beyond 1 μm, consistent with an E-type asteroid, (Barucci et al. 2005), and for asteroids 1996 PW and 1997 SE5, candidates to be extinct comets inside the Main Belt, having both moderately red and featureless spectra typical of the D-type asteroids (Hicks et al. 2000). Furthermore, the spectroscopic characterization is needed to investigate the possible relationship of the target with meteorites found on Earth.

5 Conclusion

Comets and NEOs populations are important targets both for ground based and space investigation. These small objects tell us the origin, early stages and evolution of the Solar System. Understanding the sources and nature of mineralogical and organic components and the chemical processes that led to their formation is the primary goal that can be achieved only in laboratory. Ground observations are necessary to characterize nature and surface composition of possible NEO targets for space missions. In particular it is demanding to improve the general characterization of main NEOs' families and classes (classical Amor, Apollo, Aten subclasses and binaries NEOs like 2000 DP107) (Margot et al. 2002), of comet–asteroid transition objects like 3200 Phaeton (Licando et al. 2007), and of NEOs with cometary albedos and/or orbits (Fernandez et al. 2005). Furthermore, the comparison between observations and sample analyses will provide the necessary information to define at best the spectroscopical behaviour of surface in relation with the physical and chemical properties of material present. Sample return mission must, furthermore, put the collected sample in the appropriate geo-morphological context of asteroid. This can be made by on-board instruments (e.g., camera, infrared spectrometer, radar, radio science) that will provide target characterizations on global and local scale. Despite the 35,000 meteorite samples available on Earth, none of these are linked unambiguously to the parent object. The ground truth of sample return mission to a NEO will solve it for the first time. In order to assess or not whether primitive minor bodies could have brought complex organic molecules capable of triggering the synthesis of biochemical compounds on the Earth, a minimum amount of about 10 g of sample should be collected ensuring that none chemical alteration occur during collection and transportation to Earth.

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