

Sample Return from Primitive Asteroids and Comets

A White-Paper for the NRC Planetary Science Decadal Survey, Reflecting the Viewpoints of the NASA Analysis Group CAPTEM (Curation and Analysis Planning Team for Extraterrestrial Materials)

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*This white paper has been posted on the CAPTEM website noted above and inputs to it were sought from the planetary science community at large. Numerous comments and suggestions were received from many members of this community, and resulted in substantial revisions and endorsements to this white paper.

Introduction

Much of our current understanding of the origin and history of the Solar System is based upon laboratory studies of meteorites and interplanetary dust particles which have revealed the age of the Solar System, the timescales of planetary accretion and differentiation [1], the lifetime of the solar nebula [2], the diversity and distribution of primordial organic matter [3], and the bulk composition of the Solar System for non-volatile elements [4,5]. Analyses of circumstellar and interstellar materials (stardust, also known as presolar grains) in primitive meteorites in particular have opened up a completely new branch of laboratory astrophysics, providing direct probes of stellar nucleosynthesis, galactic chemical evolution, and interstellar chemical processes [6]. However, as discussed below, there are limitations to the information that can be gleaned from meteoritic materials. Primitive asteroids and comets are comprised of materials that formed in the earliest stages of Solar System history. These objects are also likely to have preserved materials (i.e., interstellar and circumstellar dust grains) that predate the formation of the Solar System. Primitive asteroids and comets also have special importance for astrobiology and the origin of life, having contributed a major portion of water and organic matter to the early Earth. Finally, asteroids and comets pose a long term impact hazard to the Earth. An improved knowledge of the properties of potentially hazardous asteroids and comets is required as a step in developing strategies to protect the Earth from future collisions with these bodies.

Motivation for sample return

Sample return from primitive asteroids and comets is scientifically compelling and will have a major impact on our understanding of the origin and evolution of the Solar System. Sample return missions are complementary to astronomical observations and remote analyses by spacecraft; each type of study provides essential and unique information necessary to deciphering the origin and history of the solar system. Remote sensing has given a broad view of the global properties of comets and asteroids, and revealed subpopulations and compositional classes. Spacecraft analyses (including flyby, orbiting or landed missions) give opportunities to globally survey objects, reveal planetary scale compositions, and their dynamical histories. But sample return allows the ultimate level of detailed study, down to the atomic scale, with analytical precision and accuracy that far exceeds that of the best spacecraft instruments. In contrast to space-qualified instruments that must adhere to severe mass, power and reliability requirements, there are few restrictions on the size, complexity, cost, or variety of scientific apparatus that can be brought to bear on returned samples. Scientific consortia can routinely conduct sequential, coordinated studies on microscopic samples, using the best instruments available. As little as a few nanograms of material can be sufficient for complex investigations that may have implications on planetary scales. Indeed, studies of primitive, fine-grained extraterrestrial materials have played a major role in driving the spectacular advances in microanalytical techniques and instruments since Apollo. Material can be preserved for future generations of scientists who have new ideas and improved analytical techniques. Sample return is necessary for certain types of studies that simply cannot be done in any other way, such as identifying minor mineral components and describing petrographic relationships, measuring precise isotopic ratios, conducting thorough molecular studies of organic matter, determining high precision ages of materials and timescales for various processes, and establishing firm links between spectral features and material properties. These types of studies are integral to unraveling the complex histories of these bodies and, therefore, of the Solar System.

Both primitive asteroids and comets harbor valuable historical records of early Solar System and presolar processes. But these bodies originated in very different regimes of the Solar System and thus record different and complementary types of information. Below we consider the scientific rationale for sample return from primitive asteroids and comets separately.

Meteorites and interplanetary dust particles as probes of primitive Solar System bodies: Opportunities and limitations

Meteorites exhibit diversity in compositions showing that they formed or evolved in a variety of thermal and chemical regimes. Primitive meteorites are largely made up of nebular materials

and a small fraction of interstellar materials, which have undergone differing degrees of thermal and aqueous processing on their parent bodies. Such meteorites contain the oldest known Solar System solids (calcium-aluminum-rich inclusions or CAIs) and the more abundant chondrules, which typically formed a couple of million years later during transient heating events in the solar nebula.

The parent bodies of some meteorites were large enough to undergo partial or complete melting and igneous differentiation, but the least altered meteorites still retain elemental abundances remarkably close to the Solar System average. These primitive meteorites contain abundant organic matter that displays great molecular complexity and anomalous H and N isotopic compositions. Some fraction of this material likely originated in cold molecular clouds or the outermost regions of the protosolar disk. They also contain *bona fide* stardust, mineral grains which formed in the outflows of dying stars (red giants, novae, and supernovae). Presolar materials are not only direct probes of distant astrophysical environments; they are the true building blocks of the Solar System and have recorded within them the radiation, thermal, nuclear, and chemical processes that forged our planetary system. As essentially all of the elements beyond boron are formed in stars, presolar grains provide a unique way to study the origin of the elements.

Astronomical observations and spacecraft missions have helped to put laboratory studies of meteorites into context. Spacecraft encounters with five asteroids have found a remarkable structural and chemical diversity. Extended rendezvous to two S-asteroids have been performed by the Near Earth Asteroid Rendezvous (NEAR) mission to 433 Eros and the Japanese Hayabusa mission to asteroid Itokawa. Though spectrally similar, Eros appears to be dense and collisionally evolved [7], whereas Itokawa is a classic rubble pile [8]. The Dawn spacecraft is now en route to two large asteroids: the differentiated asteroid Vesta and the potentially primitive, ice-rich Ceres. This diversity in asteroid types is clearly evident in the variety of spectral signatures of asteroids, which vary roughly according to their distance from the Sun. In a few cases, asteroids have been spectrally matched with meteorites, such as the linkage between basaltic achondrite (HED) meteorites and the asteroid Vesta [9].

However, reflectance spectra of most asteroids are relatively featureless leaving their mineralogy and potential links to meteorites uncertain. To make matters worse, the surfaces of asteroids are covered with regolith that has been chemically and physically altered by radiation, condensation, and impact processes which are collectively called “space weathering.” Space weathering strongly affects asteroid and comet spectra in ways that are not fully quantified. In addition, it is clear that the meteorite collection is an incomplete and biased sampling of the asteroid belt. Meteorites originating from portions of the asteroid belt near secular resonances and mean-motion resonances with Jupiter are the most efficiently delivered to the Earth [10]. Thus, while meteorites contain extremely valuable records of early Solar System materials and processes, significant uncertainties remain in how they fit in with the overall structure of the inner Solar System and the nature and composition of most asteroids is still poorly known.

Cosmic dust collected in the Earth’s stratosphere provides an additional and unique sampling of both comets and asteroids. Some cosmic dust particles are inferred to have asteroidal origins based on their hydrated mineralogy. However, most of these particles differ from meteorites in their mineralogy, spectral characteristics, and high abundances of carbon. Other cosmic dust particles have properties similar to those of comets inferred from remote sensing and spacecraft encounters [11]. Despite their small size (10^{-9} g) they have near solar elemental abundances, and are fragile assemblages of sub- μm amorphous and crystalline anhydrous silicates, sulfides, and other minerals bound together by a carbonaceous matrix. These putative ‘cometary’ interplanetary dust particles (IDPs) appear to have escaped much of the parent body processing that has affected meteorite parent bodies (asteroids) and may represent the least altered remnants of the Solar System starting materials [12]. This inference is borne out by the extraordinarily high abundances of stardust and interstellar materials, exceeding 1 wt% in some IDPs [13,14].

Owing to uncertainty in their sources it is difficult to put the properties of IDPs into a global context. Unlike meteorites, interplanetary dust particles are not subject to strong dynamical selection effects and can be delivered to Earth from any dust producing body. Constraints on the orbital velocities of IDPs indicate that comparable proportions derive from asteroids and comets,

in broad agreement with astronomical observations and models of the interplanetary dust complex (15). Although their provenance is unknown, the unique characteristics of IDPs indicate that meteorites represent a limited sampling of the most primitive asteroids.

The case for sample return from primitive asteroids

Returning samples from a primitive asteroid would have a strong impact on scientific issues that are of central importance to planetary science. While studies of meteorites have laid the foundation for our understanding of the origin of the Solar System, significant gaps in our knowledge remain. Most importantly, meteorites are a selective and incomplete sampling of the asteroid belt, and the places of origin of the vast majority of meteorites are poorly constrained. Below we outline some high impact studies that would benefit through the analysis of appropriately selected and sampled primitive asteroidal materials.

What is the relationship between outer-belt asteroids and comets? Several outer-belt asteroids have exhibited episodic activity similar to comets [16]. The volatile loss is attributed to sublimation of water ice heated by solar radiation. These ‘main belt comets’ likely formed within the asteroid belt, and may thus represent an intermediate stage of evolution between comets and the parent bodies of primitive meteorites. The sublimation of water ice indicates that at least the surfaces of these objects were never warm enough to sustain liquid water, one of the principle alteration pathways for primitive meteorites. These asteroids thus represent a class of primitive material not represented by meteorites, but may be related to IDPs. These asteroids may be fine-grained, fragile assemblages of anhydrous minerals and ice; material that could not survive passage through the Earth’s atmosphere as macroscopic (meteorite-sized) bodies. Outer-belt D- and P-type asteroids also bear spectral similarities to comet nuclei and Kuiper Belt objects (KBOs; [17]). These asteroids have low albedos and are thought to be rich in organic matter and water. These enigmatic outer-belt asteroids are important because they preserve unique records of the transition between the Solar System starting materials and the origins of the planets. Key questions to be addressed by a sample return from an outer belt or comet-like asteroid:

- What processes drive the cometary-like activity?
- Have these asteroids experienced aqueous alteration? Is the extent of water:rock interactions on asteroids sensitive to location within the asteroid belt?
- What is the nature of organic matter in these asteroids?
- Are outer-belt asteroids the parent bodies of IDPs?

What is the origin and evolution of organic matter in the Solar System? In situ collection of material from a carbon-rich asteroid could provide the first truly pristine sample of primordial organic matter. Previous studies have been limited by uncertainty in the origins of some components owing to the potential for terrestrial contamination. During their residence on Earth, meteorites can be exposed to microbes and may lose volatile organics and water soluble phases. The origins of some organic compounds in meteorites can be traced back to processes occurring in a presolar cold molecular cloud, and have since been altered by nebular and parent body processes [18,19]. Organic matter thus offers a complex but powerful narrative of processes at work in a wide range of astrophysical environments that shaped the Solar System starting materials from the earliest stages. While extensive work has been done on meteoritic organic matter, significant uncertainty remains as to whether it mainly derived from interstellar, nebular, or parent body processes. For example, isotopic signatures of α amino acids were likely established in a cold molecular cloud, but the molecules themselves may have been produced in aqueously mediated reactions in an asteroid [6]. Outer-belt asteroids that have not experienced aqueous alteration are excellent sample return targets because they may preserve an earlier stage in the evolution of Solar System organic matter. Key questions to be addressed by sample return from a carbon-rich asteroid include:

- What processes created or destroyed organic matter in the solar nebula?
- To what extent did aqueous and thermal processes in asteroids affect organic matter?
- Are some organic compounds in asteroids unaltered samples of interstellar matter?

What constraints can be placed on the thermal and dynamical evolution of the early Solar System? The asteroid belt displays compositional gradients in asteroid spectra, and these trends may

be reflected in compositional variations among meteorites. In particular, various classes of meteorites appear to be depleted in volatile elements relative to the benchmark CI chondrites which match the composition of the solar photosphere for most elements, excluding H, Li, C, N, O and noble gases. Variations are also evident in the wide range of oxidation states recorded among meteorites. These compositional variations were established and maintained over a relatively narrow range of the nebula, which implies the inner nebula was not well mixed. On the other hand, meteorites incorporated materials originating from throughout the disk, from the inner solar system (CAIs and possibly chondrules) to the cold outer disk (anomalous organic compounds), indicating large-scale cycling of material throughout the solar system. Sampling asteroids can help reconcile these seemingly contradictory observations. This would establish a spatial reference for key parameters used in models of the early Solar System, including local oxygen isotopic reservoirs, the abundance of volatile elements, the oxidation state, the nebular thermal environment, and the surviving fraction of presolar materials. Key questions to be addressed by this study:

- How did refractory phases and delicate organic matter come to coexist in meteorite matrices?
- What were the thermal processes that gave rise to CAIs and chondrules and where did they occur in the disk?
- What is the origin of the oxygen isotopic variability among planetary materials?
- What are the origins of short-lived nuclides in the early Solar System, and were they uniformly distributed?

How is space weathering manifested on the surfaces of asteroids? A range of processes are potential space weathering agents, including solar wind and solar flare ion implantation, UV photolysis, cosmic ray bombardment, and micrometeorite impact [20]. Space weathering can lead to loss of volatile surface ice while producing refractory organic material. Experiments show that ion irradiation of silicate minerals leads to reduction of iron and simulated micrometeorite impacts have produced nanophase iron in olivine grains. All of these processes may contribute to the reddening of asteroid spectra. There is a need to obtain pristine surface samples of a well-characterized asteroid to establish the mechanisms of space weathering. This would provide an anchor for spectral interpretation of the compositions and interrelationships of numerous asteroids and establishing links between meteorites and their parent bodies. Careful selection and sampling of asteroidal surface material is essential to solving these issues, but will be strengthened by continued spectroscopic surveys of asteroids, both by ground-based and in situ analyses. Key questions to be addressed by a better understanding of space weathering:

- What specific mechanisms are involved in the alteration of the spectra of asteroidal surfaces during space weathering?
- From where in the asteroid belt did primitive meteorites originate?
- Which parts of the asteroid belt have yet to be sampled by meteorites?

The case for sample return from comets

Short-period comets are enigmatic primitive objects, originating more than an order of magnitude farther from the Sun than asteroids and making only brief transits to the inner Solar System. It is the fact that these comets formed so far from the Sun (> 40 AU) that accounts for their great scientific value. Whereas large fractions of meteoritic materials formed at high temperatures, volatile ices in comets constrain their accretion temperature to less than 25 K [21]. Comets are distinguished by their high abundances of water ice, other volatiles, and carbon. Unlike asteroids, comets are unlikely to have been thermally or aqueously altered after accretion, and the size and abundance of radionuclides of most Kuiper belt objects were insufficient for differentiation. Comets are thus likely to be our closest link to the original Solar System starting materials.

Astronomical observations of comets show diversity in their chemistry and mineralogy, but they generally contain abundant fine-grained amorphous and crystalline silicates. Spacecraft visits to comet Halley supported these findings, showing it to be dominated by sub- μm silicates and organic grains [22]. These observations led some to view comets as essentially pristine aggregates of interstellar materials. We now know, from examination of the samples of Comet

81P/Wild 2 collected and delivered to Earth by the Stardust spacecraft, that the situation is much more complex, as discussed further below.

Lessons learned from the Stardust mission

The NASA Stardust mission successfully returned the first direct samples of a comet to the Earth in January 2006. Upon safely landing, the main mission of Stardust began, with a furious year of participation by over 150 scientists from around the globe. Although less than 1 microgram of material has been analyzed so far, Stardust samples yielded several major findings.

- Refractory grains have been identified, bearing remarkable textural, mineralogical, and isotopic resemblance to CAIs, chondrules, and AOs [23,24].
- Comet Wild 2 appears to be distinct mineralogically from chondritic porous IDPs, which have long been thought to originate in comets [25,26].
- The presence of refractory grains, high concentrations of noble gases and high degree of crystallinity of silicates all point toward a surprisingly efficient mixing of inner solar system material into the Kuiper belt in early history of the solar system [27].
- Some Stardust particles appear to contain extremely high concentrations of noble gases, possibly higher than any other known extraterrestrial material [28].
- The abundance of fine-grained materials and presolar grains were much lower than expected – lower even than some meteorites [29].
- Intact organic matter is present, but was surprisingly difficult to find [30].

Though Stardust fully succeeded in its mission objectives, there were several important shortcomings that have left open key science questions. Samples were collected into silica aerogel and Al foils at 6.1 km/s, leaving little chance for volatiles and organic matter to survive.

Sample return from comets in the context of Stardust

The surprises, successes, and shortcomings of Stardust, the first sample return from a comet, have given even greater impetus to pursue an improved cometary sample return strategy. High priority is given to returning undamaged samples, intact volatiles, and uncontaminated organic matter. Several key scientific problems would be immediately impacted by the return of such a sample:

What fraction of cometary materials has presolar (interstellar) origins and what fraction has solar system origins? Isotopic studies have shown that only a minor population of Stardust samples had interstellar origins. However, presolar grains are mostly sub- μm in size, and fine grained materials may have been preferentially destroyed during the hypervelocity impact capture process. This capture process also blurred the distinction between the collection medium (amorphous silica) and amorphous silicates, which were expected to be found in abundance. It is thus unclear what the true abundance of presolar materials was in Wild 2 and what was the nature and origin of its silicate dust. These are among the most vexing questions left unanswered by the Stardust mission. These issues have major implications for the formation, cycling, and evolution of matter in interstellar space and young planetary systems. The above questions can readily be answered by textural, chemical, and isotopic measurements of submicrometer grains, which are already routinely done with advanced instrumentation in several laboratories. Key questions to be addressed by this study:

- What is the abundance, nature, and origin of amorphous silicates in comets? Are cometary silicates circumstellar grains, irradiated dust grains, or solar nebula condensates?
- Do some comets preserve higher concentrations of presolar materials than others?
- Are there comets that are truly pristine aggregates of interstellar materials?

What can comets tell us about the large-scale dynamical evolution of the Solar System? Surprisingly, one of the first particles extracted from the Stardust collector turned out to be a refractory mineral assemblage akin to a CAI. Isotopic, chemical, and mineralogical studies of this and other refractory Stardust samples show similarities to refractory inclusions in meteorites. In addition, so far all crystalline silicates have O isotopic compositions within the range of Solar System materials. The best explanation is that these materials formed within the inner Solar System at high temperatures and were subsequently transported ~ 40 AU from the Sun to become incorporated into accreting KBOs. It will be important to determine whether other comets also harbor abundant high temperature minerals in order to constrain the extent of radial mixing of material

from the inner hot solar nebula to the outermost regions of the protoplanetary disk. Key questions to be addressed by a this study:

- From what regions of the solar nebula did cometary minerals originate?
- What was the mechanism of transport – bipolar outflow or turbulent diffusion?
- Do cometary refractory minerals harbor extinct radionuclides and O isotopic anomalies?

What fraction of cometary volatiles and organics originated in cold molecular clouds or in the solar nebula? Cometary organics and volatiles are of particular interest because they ought to record the clearest link to the cold molecular cloud phase that immediately preceded the origin of the Solar System. Further, comets preserve evidence of the earliest stages of evolution of organic matter in the Solar System prior to incorporation into asteroids. H and N isotopic anomalies have been observed spectroscopically in some simple cometary volatiles and in Stardust samples, indicating potential origins a cold molecular cloud. However, conditions in the outer protosolar disk may have been similar to those of the preceding cold cloud phase, raising the possibility that similar chemical and isotopic fractionation processes could have occurred there. The origins of these materials should be somewhat simpler to decipher in comparison to asteroidal materials which experienced significantly more vigorous nebular and parent body processing. Key questions to be addressed by return of cometary volatiles and organic matter:

- Did cometary organics and ices originate in interstellar space or the outer solar nebula?
- Do cometary organics resemble those found in meteorites?
- Did the outer solar nebula promote chemical evolution and isotopic fractionation?

Did comets experience aqueous alteration? Deconvolution of complex infrared spectra obtained from the Deep Impact mission ejecta suggests that clay and carbonate minerals are present in comet Tempel 2. In fact, cometary materials are likely to be amenable to aqueous alteration, as fine grained amorphous silicates can be altered by water even at room temperature. However comets are not thought to have maintained conditions necessary to sustain liquid water. The only way to definitively identify these minerals is by laboratory analysis of returned samples. Key questions related to the potential for aqueous activity within comets:

- What was the heat source to melt the ice?
- What affect does aqueous alteration have on cometary organic compounds?

Summary

The analysis of comet dust collected by the NASA Stardust mission yielded several revolutionary findings regarding the origin and history of comets, including the presence of refractory minerals and evidence of extensive mixing of materials the early Solar System. But comet flyby missions show a diversity of comet morphologies, and remote sensing shows compositional differences, particularly between short-period (Kuiper belt) comets and long-period (Oort cloud) comets. It is unknown how representative the first comet sample return target was to the overall comet population. A successor comet sample return mission is essential to resolving fundamental science questions raised by Stardust regarding the origins, histories, and diversity of cometary materials. Asteroid sample return will have similarly high impact, by revealing the earliest stages of planetary formation from primordial materials, strengthening the link between meteorites and their parent bodies, and clarifying the relationship of the most primitive asteroids to comets. Collection of organic matter from both primitive asteroids and comets will provide the opportunity to examine some of the earliest pre-biotic organic matter of our Solar System, material that may have been the starting materials for the origin of life on Earth.

References:

- [1] Wadhwa M & Russell SS (2000) Timescales of accretion and differentiation in the early solar system. In Protostars and Planets IV, Univ. Ariz. Press, pp. 995–1018.
- [2] Huss GR et al. 2001. Aluminum-26 in calcium-aluminum-rich inclusions and chondrules from unequilibrated ordinary chondrites. *Met. Planet. Sci.* 36: 975.
- [3] Pizzarello S et al. 2006. The nature and distribution of organic matter in carbonaceous chondrites and interplanetary dust. In Meteorites and the Early Solar System II, Univ. Ariz. Press.

- [4] Anders E, & Grevesse N 1989. Abundances of the elements: meteoritic and solar. *Geochim. Cosmochim. Acta* 53: 197.
- [5] Palme H & Jones AP 2003. Solar system abundances of the elements. In *Meteorites, Planets, and Comets*, Vol. 1 *Treatise on Geochemistry*, Elsevier-Pergamon, Oxford, pp. 41–61.
- [6] Zinner E 2007. Presolar grains. In *Meteorites, Planets, and Comets*, Vol. 1 *Treatise on Geochemistry*, 2nd Ed., Elsevier, Oxford.
- [7] Asphaug E 2009. Growth and evolution of asteroids. *Ann. Rev. Earth Planet. Sci.* 37: 413.
- [8] Fujiwara A et al. 2006. The rubble-pile asteroid Itokawa as observed by Hayabusa. *Science* 312: 1330.
- [9] Keil K 2002. Geological history of asteroid 4 Vesta: The “smallest terrestrial planet.” In *Asteroids III*, Univ. Ariz. Press, pp. 573–584.
- [10] Morbidelli A et al. 2002. Origin and evolution of near-Earth objects. In *Asteroids III*, Univ. Ariz. Press, 409.
- [11] Bradley JP 2007. Interplanetary dust particles. In *Meteorites, Planets, and Comets*, Vol. 1 *Treatise on Geochemistry*, 2nd Ed.
- [12] Messenger S et al. 2006. The population of starting materials available for Solar System construction. In *Meteorites and the Early Solar System II*, Univ. Ariz. Press, 187–208.
- [13] Messenger S 2000. Identification of molecular cloud material in interplanetary dust. *Nature* 404: 968.
- [14] Busemann H. et al. 2009. Ultra-primitive dust from comet 26P/Grigg-Skjellerup. *Earth Planet. Sci. Lett.*, in press.
- [15] Joswiak DJ et al. 2000. Characteristics of asteroidal and cometary IDPs obtained from stratospheric collectors: summary of measured He release temperatures, velocities, and descriptive mineralogy. *LPS* 31, #1500.
- [16] Hsieh HH & Jewitt D 2006. A population of comets in the main asteroid belt. *Science* 312: 561.
- [17] Burbine TH et al. 2002. Meteoritic parent bodies: their number and identification. In *Asteroids III*, Univ. Ariz. Press, pp. 653–667.
- [18] Busemann et al. 2006. Interstellar Chemistry Recorded in Organic Matter from Primitive Meteorites, *Science* 312: 727.
- [19] Nakamura-Messenger K et al. 2006. Organic Globules in the Tagish Lake Meteorite: Remnants of the Protosolar Disk. *Science* 314: 1439.
- [20] Chapman CR 2004. Space weathering of asteroid surfaces. *Ann. Rev. Earth. Planet. Sci.* 32: 539.
- [21] Notesco G et al. 2003. Gas trapping in water ice at very low deposition rates and implications for comets. *Icarus* 162: 183.
- [22] Brownlee DE 2007. Comets. In *Meteorites, Planets, and Comets*, Vol. 1 *Treatise on Geochemistry*, 2nd Ed., Elsevier, Oxford.
- [23] Simon SB et al. 2008. A refractory inclusion returned by Stardust from comet 81P/Wild 2. *Met. Planet. Sci.* 43: 1861.
- [24] Nakamura T et al. (2008) Chondrule-like objects in short-period comet 81P/Wild 2. *Science* 321: 1664.
- [25] Zolensky ME et al. 2006. Mineralogy and petrology of Comet 81/Wild-2 nucleus samples. *Science* 314: 1735.
- [26] Ishii HA et al. 2008. Comparison of Comet 81P/Wild 2 dust with interplanetary dust from comets. *Science* 319: 447.
- [27] Westphal AJ et al. 2009. Mixing fraction of inner Solar System material in comet 81P/Wild2. *Astrophysical Journal* 694: 18-28.
- [28] Marty B et al. 2008. Helium and Neon Abundances and Compositions in Cometary Matter, *Science* 319: 75
- [29] McKeegan KD et al. 2006. Isotopic compositions of cometary matter returned by Stardust. *Science* 314: 1724.
- [30] Sandford SA et al. 2006. Organics captured from Comet 81/Wild 2 by the Stardust spacecraft. *Science* 314: 1720.