Sample return of primitive matter from the outer Solar System

P. Vernazza, P. Beck, Ottaviano Ruesch, A. Bischoff, L. Bonal, G. Brennecka, R. Brunetto, H. Busemann, J. Carter, C. Carli, et al.

Experimental Astronomy
https://doi.org/10.1007/s10686-021-09811-y

ORIGINAL ARTICLE

Sample return of primitive matter from the outer Solar System

P. Vernazza, et al. ***[full author details at the end of the article]***

Received: 21 July 2020 / Accepted: 15 October 2021

Abstract
The last thirty years of cosmochemistry and planetary science have shown that one major Solar System reservoir is vastly undersampled in the available suite of extra-terrestrial materials, namely small bodies that formed in the outer Solar System (>10 AU). Because various dynamical evolutionary processes have modified their initial orbits (e.g., giant planet migration, resonances), these objects can be found today across the entire Solar System as P/D near-Earth and main-belt asteroids, Jupiter and Neptune Trojans, comets, Centaurs, and small (diameter < 200 km) trans-Neptunian objects. This reservoir is of tremendous interest, as it is recognized as the least processed since the dawn of the Solar System and thus the closest to the starting materials from which the Solar System formed. Some of the next major breakthroughs in planetary science will come from studying outer Solar System samples (volatiles and refractory constituents) in the laboratory. Yet, this can only be achieved by an L-class mission that directly collects and returns to Earth materials from this reservoir. It is thus not surprising that two White Papers advocating a sample return mission of a primitive Solar System small body (ideally a comet) were submitted to ESA in response to its Voyage 2050 call for ideas for future L-class missions in the 2035-2050 time frame. One of these two White Papers is presented in this article.

Keywords Sample return · Primitive small body · Comets · P/D type asteroids · Cryogenic

1 Introduction

Constraints on the formation of a planetary system can be derived from observations of interstellar clouds, star-forming regions, and exoplanets, enabling the characterization of the diversity of ingredients, processes, and products of stellar formation. The study of nascent extra-solar stellar systems and their planets is, however, limited by our inability to follow the formation processes of a single system over the entire formation interval, which takes millions of years. In addition, since these are distant systems, it is not possible to examine all the processes, especially those that leave specific imprints in the chemical, isotopic, and structural makeup of dust and minerals, i.e., at micrometer- and submicrometer-scales [1]. The study of our Solar System provides the complementary information and in particular a complete chronology of the major events that shaped it and that resulted in the formation of an inhabited planetary system. Confronting the astrophysical view of planet formation as observed across the Galaxy to that derived for the Solar System is of prime importance to assess whether the processes governing the formation of our planetary system were the exception or the rule.

For that purpose, extra-terrestrial samples, which date from the early stages of the Solar System, are of fundamental importance. As a matter of fact, the most detailed information on the processes, conditions, and timescales of the early history of the Solar System has so far come from the study of extra-terrestrial samples in Earth-based laboratories. Most of them are delivered naturally to Earth and occur in the form of rocks (meteorites), fragments (micrometeorites), or dust (interplanetary dust particles, IDPs). This suite of samples is among the most studied in Earth and Planetary Science laboratories and has enabled us to probe some of the constituents of the solar accretion disc (chondrules, refractory inclusions, matrix, macromolecular organics), to examine in detail the first steps of planetesimal formation (agglomeration of dust, impacts, differentiation) and to determine the timing of different processes (absolute and relative).

However, cosmochemistry (the science of extra-terrestrial samples) is tied to the type of sample available for laboratory studies. The present day cosmochemical view of Solar System formation is limited by biases inherent to the fact that most samples are collected passively, at 1 AU (AU). First, direct information on the origin of most samples within the Solar System is generally lost. Second, the Earth's atmosphere plays an important role in filtering out most of the fine-grained material (micrometeorites and IDPs) against strongly lithified objects (meteorites). Last, the volatiles (ices) and most semi-volatile (salts) species are largely lost during the orbital transfer from the source region to the Earth.

The last thirty years of cosmochemistry and planetary science have shown that one major Solar System reservoir is vastly undersampled in the available suite of extra-terrestrial materials, namely small bodies that formed in the outer Solar System (>10 AU). Because various dynamical evolutionary processes have modified their initial orbits (e.g., giant planet migration, resonances), these objects can be found today across the entire Solar System as P/D near-Earth and main-belt asteroids, Jupiter and Neptune Trojans, comets, Centaurs, and small (diameter < 200 km) trans-Neptunian objects (TNOs). This reservoir is of tremendous interest, as it is recognized as the least processed since the dawn of the Solar System and thus the closest to the starting materials from which the Solar System formed. This is underlined by the extremely interesting results obtained by in-situ studies of isotopic compositions of matter from comet 67P/Churyumov-Gerasimenko by ESA's Rosetta mission (see [2] for a review), and from laboratory studies of anhydrous chondritic porous interplanetary dust particles (CP-IDPs; [3, 4]), ultra-carbonaceous Antarctic micrometeorites (UCCAMs; [5]), and matter from comet 81P/Wild 2 returned to Earth in 2006 by NASA's Stardust mission [6].

The next major breakthroughs in planetary science will come from studying outer Solar System samples in terrestrial laboratories, but this can only be achieved by an L-class mission that directly collects and returns to Earth materials from this reservoir. The proposed strategy consists of 1) a direct trajectory to the rendezvous target, 2) a reconnaissance and characterization of the terrain for sample context with an orbiter payload including an optical camera, a near-infrared spectrometer, and a thermal infrared camera, 3) collection of surface/subsurface samples (at least two locations) that are volatile and dust rich, and 4) return of the samples to Earth. The re-entry capsule must be able to conserve the samples at cryogenic temperature. The selected target should be as primitive as possible which might exclude near-Earth objects from the candidate list as they have been too processed or altered by their close passages to the Sun. Comets and P/D main-belt asteroids including main-belt comets would then appear as the most accessible and scientifically valuable targets, with comets being our preferred targets because of their activity that can be used to characterize the volatiles and also because their surface should be more "primitive" due to the involved erosion processes.

2 Deciphering the birth of the Solar System

For decades the Solar System was assumed to be the prototype for planetary system formation. With the detection of over 4000 confirmed exoplanets, it has become apparent that many planetary systems exist that differ substantially in their structural properties from our Solar System, most notably with respect to the distribution of the planetary masses in the system. Nevertheless, the formation of the Solar System is still of special interest for several reasons. First, it is only for the Solar System that we can directly examine material that is left over from the formation process in the form of meteorites and interplanetary dust particles. Second, only for the Solar System we do have detailed structural and temporal information about the entire system including its smaller bodies. Last but not least, it is only for the Solar System that we know for sure that life exists [7]. Hereafter, we summarize our current understanding of the formation and early evolution of the Solar System, which is derived to a large extent from the study of extra-terrestrial samples (meteorites, interplanetary dust particles) and of their parent bodies. These are, with a few exceptions, the small bodies (asteroids, giant planet Trojans and irregular satellites, Kuiper belt objects, and comets).

The protosun and solar nebula were formed ~4.6 Gyrs ago (as attested by U-Pb dating of Ca-Al-rich inclusions in chondritic meteorites; [8–10]) by the self-gravitational collapse of a dense molecular cloud core, like new stars being formed today in regions of active star formation (Fig. 1). The population of solid materials initially present in the molecular cloud from which the Solar System formed comprised materials with a variety of origins. An important constituent is interstellar dust, most of which is assumed to have formed in the interstellar medium (ISM) [11], while stardust, mostly from asymptotic giant branch (AGB) stars and supernovae, identified as so-called presolar grains in primitive Solar System materials [12], was estimated to account for a few percent of interstellar dust

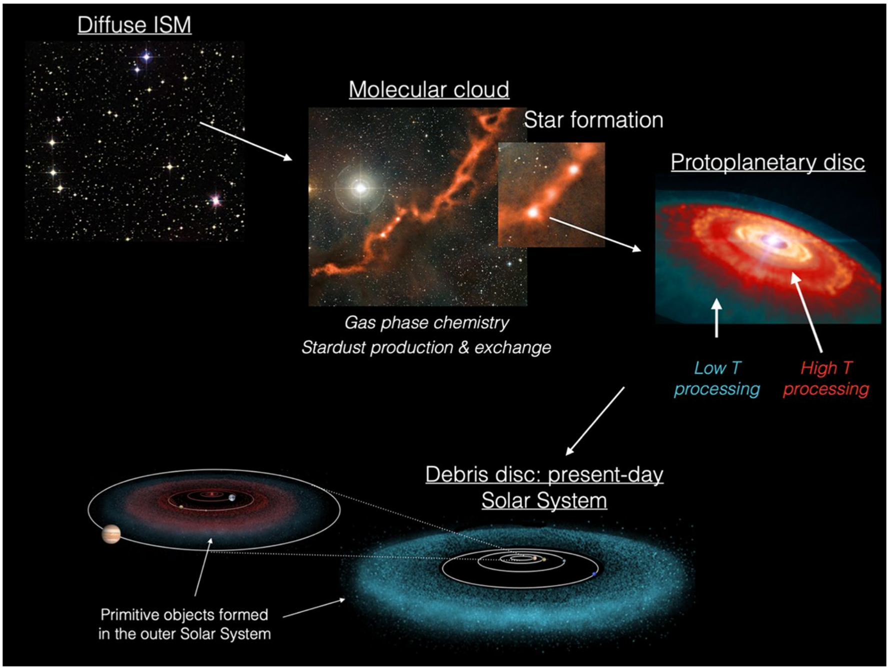

Fig. 1 Postulated sequence of events tracing the formation and early evolution of the Solar System. The most primitive Solar System bodies were born small (diameter < 250 km) and far from the Sun. After their formation, some were injected into the inner Solar System as a consequence of giant planet migration (Nice model)

[13]. Interstellar dust grains have been altered to various degrees by high-energy radiations while in the diffuse ISM.

According to spectroscopic observations of nascent extra-solar systems and the dense cloud environments in which they form, the starting materials included small (<1 μm diameter) silicate grains that were essentially amorphous in nature (e.g., [14]), carbonaceous grains [15, 16], and a variety of ice species and complex organic molecules.

When the solar nebula evolved into a Keplerian disc, chemical differentiation began. The density and temperature profiles of the disc (inversely correlated with heliocentric distance; Fig. 1) led to various degrees of chemical, isotopic, and mineralogical alteration of the primordial materials as a function of heliocentric distance. While the inner parts of the disc reached temperatures high enough to vaporize silicates, the outer portions of the nebula remained at cryogenic temperatures. It follows that during the protoplanetary disc phase, the starting materials were best preserved in bodies that formed in the outer Solar System. Furthermore, the simultaneous presence of low- and high- temperature mineral phases – believed to have formed far from and close to the Sun, respectively, i.e. in chondritic (primitive) meteorites and in comets [17–19], implies that radial mixing in the protosolar disc played a prominent role in shaping the composition of small bodies [20].

In less than 1 Myr and still during the disc phase, the first generations of bodies, the planetesimals, formed. These included small bodies such as the parent bodies of iron and achondritic meteorites (like the terrestrial planets, these small bodies underwent differentiation) but also the massive cores of planets such as Jupiter. An early formation of Jupiter's massive core is currently proposed as the origin of the observed isotopic dichotomy between non-carbonaceous and carbonaceous chondrites (e.g., [21]). The last generations of bodies to form were the parent bodies of chondritic meteorites in the inner Solar System (<~10 AU) and of interplanetary dust particles in the outer Solar System (> ~ 10 AU; [22]) as well as the terrestrial planets. Concerning small bodies, recent modelling work [22] suggests that the timescale of completion of formation was positively correlated with their formation location. Accretion ended earlier inward of the snow line (≈2Myr for ordinary chondrite parent bodies; [23, 24]) than just beyond Jupiter (3–4 Myr, CM-like bodies), which itself stopped earlier than for IDP-like objects farther out (>5 Myr for bodies at ≈8 AU and > 6 Myr at ≈20 AU). Given that the early thermal evolution of small bodies was mainly governed by the decay of the short-lived radionuclide ^{26}Al (half life of ~0.7 Myr), this implies that a significant fraction of the starting materials escaped global scale parent-body alteration (such as differentiation, aqueous alteration, and/or thermal metamorphism) in bodies that formed at large heliocentric distances, namely among IDP-like bodies.

Small bodies and their associated fragments that formed farther from the Sun thus appear as the most pristine Solar System objects because they formed in the coldest region of the protoplanetary disc and because they formed sufficiently late to be little affected by ^{26}Al heating. Spectroscopic surveys of small bodies ([25], see [26]) currently imply that chondritic porous IDPs are the most likely samples for most of these bodies. Although mineralogically different from IDPs, also the Tagish Lake meteorite might be a fragment of a small body that formed in the outer region of the protoplanetary disc [27, 28].

The present orbits and optical colors of small bodies further imply that the migration of giant planets governed the subsequent dynamical evolution of the Solar System and thus modified its initial architecture (e.g., [29–33]). One important outcome from these models, which is further supported by current spectroscopic surveys ([26]; Figs. 1 and 2), is that primitive trans-Neptunian objects were inserted in the inner Solar System and can now be recognized as P/D near-Earth and main-belt asteroids and as Jupiter Trojans in addition to comets, Centaurs, and present trans-Neptunian objects.

Whereas primitive IDP-like small bodies are - by far - the largest population of small bodies (Fig. 3), they are the least understood due to the fact that we do NOT possess representative and unaltered samples (at least cm-scale) of these objects in our collections. Bodies that were formed in the outer Solar System should therefore be considered as prime targets for Solar System exploration, and in particular in the framework of a sample return mission. Laboratory analysis of samples of these bodies would provide a major breakthrough in our understanding of Solar System formation and *the path to an inhabited planetary system*.

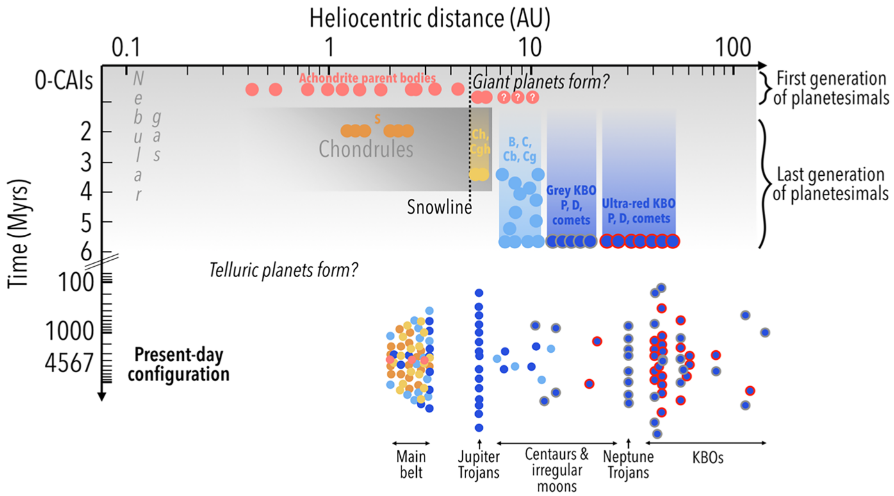

Fig. 2 (from [22]): Postulated sequence of events tracing the time, place, and duration of formation of small bodies (top) to present-day observed characteristics (bottom; vertical spread reproducing roughly the distribution of orbital inclinations). The accretion duration is shown as gradient boxes ending at the fully formed bodies. Numerical simulations suggest that volatile-rich IDP-like bodies (blue dots; B, C, Cb, Cg, P, D, comets, grey and ultra-red KBOs) accreted their outer layers after 5-6 Myrs

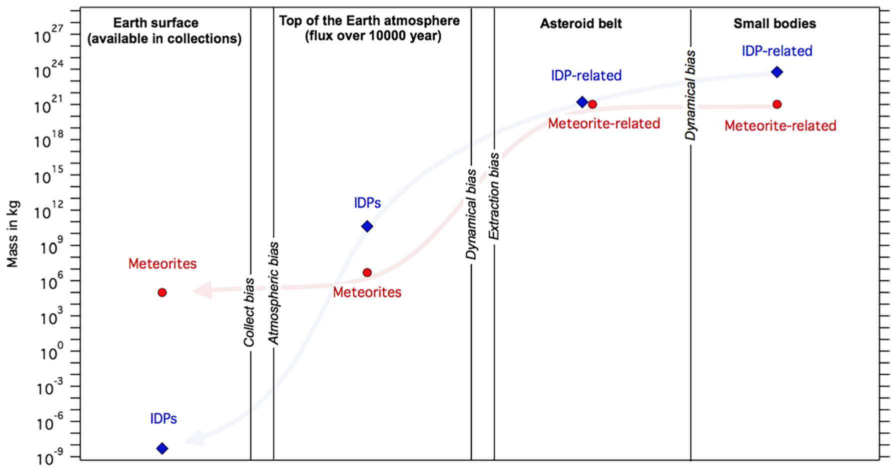

Fig. 3 The enormous bias in our sampling of Solar System small bodies. While the small body population is dominated by IDP-like objects with respect to meteorite-like ones by an estimated factor of at least 500, our collection of Solar System materials is dominated by meteorites by a factor of about 10^{14} against IDPs (in mass). This implies that we have so far only a very limited sampling of the initial constituents of the Solar System and of the small body population in general

In a collective approach, ground and space observers and astro/cosmochemists identified the following top-level science objectives that justify a sample return mission of a primitive small body:

- What is the path to an inhabited planetary system?
- What were the initial ingredients of the Solar System and how were these ingredients distributed around the young Sun?
- What is the fraction of presolar material that survived until today in outer Solar System bodies?
- How diverse was the origin of the starting materials and what was the environment of the pre-solar cloud core?
- What is the pathway of life-forming elements (C,H,N,O) from the interstellar medium to the Solar System?
- How and when did planetesimals accrete in the outer Solar System?

3 Extra-terrestrial samples: A partial and biased view of Solar System building blocks

The suite of extra-terrestrial materials offers a unique opportunity to study early Solar System processes in the laboratory, and to understand the nature of the small bodies' population. Still, the science value of these samples depends on our understanding of where they come from (parent bodies) and whether or not they sample all reservoirs of early Solar System materials.

In the following, we will describe briefly the nature of extra-terrestrial materials and present how they sample the small bodies population.

3.1 Meteorites are not representative samples of primitive small bodies

The most detailed information on the processes, conditions, and timescales of the early history of the Solar System has so far come from the study of meteorites. This stems from the fact that they represent more than 99.9% of the mass of extra-terrestrial materials in our collections (Fig. 3) and also because they have been studied in the laboratory for a much longer time than IDPs.

Meteorites have been classified into around 50 compositional groups. Such diversity results from differences in the nature of the constituents that were accreted onto the parent bodies and differences in the time of accretion (which impacted the early thermal evolution). Meteorites are classified into chondrites (from undifferentiated bodies) and achondrites (from differentiated parent bodies). In addition to preserving the earliest nebular condensates, the least-altered meteorites (some chondrites) contain traces of the starting materials, including interstellar dust grains and molecular cloud material. The most primitive meteorites contain small concentrations (ppb to ~200 ppm) of presolar grains that formed around evolved stars and in the ejecta of stellar explosions [12]. Known presolar minerals with a stellar origin are silicon carbide, graphite, silicon nitride, oxides (e.g., Al_2O_3 and $MgAl_2O_4$), and various silicates.

However, even the most primitive meteorites are comprised almost entirely of secondary materials formed within the solar nebula or their parent bodies. The most notable of these secondary materials are chondrules (mm-sized silicate spherules), which are the result of a process that converted most of the nebular solids into molten spherules. The chondrule-formation process overprinted earlier generations of solids.

Notably, meteorites are rocks, and therefore experienced a lithification process, that agglutinated components into a cohesive sample. It is currently understood that this lithification process was mainly driven by the early thermal evolution of the parent body, which experienced early heating via the radioactive decay of ^{26}Al and thus processes such as differentiation, metamorphism and aqueous alteration. Impact compaction may have played a role as well [34–37]. As a consequence of the early thermal evolution of their parent bodies, none of the currently known meteorites can be considered as truly *primitive* [35, 38–41]. Another supporting evidence for the fact that carbonaceous chondrites are processed material is that most of them are breccias (e.g., [42–44]). After their parent bodies accreted, they experienced numerous collisions that led to the mixing of different types of lithologies, sometimes contemporaneous with aqueous alteration [45]. Finally, note that impact-related compaction may have also played a role in the lithification of meteorites (e.g., [34, 46, 47]).

The Tagish Lake carbonaceous chondrite has been proposed as a sample of a D-type object, and as such has been considered as one of the most primitive Solar System samples. However, it cannot be considered as primitive protoplanetary disc material given that this sample was strongly altered by the action of liquid water on its parent body. Tagish Lake might be a fragment of the aqueously altered core of an IDP-like asteroid [28] that formed in the outer region of the Solar System, beyond the orbits of Uranus and Neptune, or possibly even in the Kuiper belt [27]. Tagish Lake is very C-rich (4-5%), and has a high porosity and unusually low contents of chondrules and calcium-aluminum-rich inclusions (CAIs; [48]). However, presolar silicate abundances are low, the result of aqueous alteration on the parent body [49]. CP-IDPs have much higher presolar silicate abundances, which are comparable to those observed in matter from comet 81P/Wild 2 [49]. CP-IDPs can thus be considered to represent more primitive material than the Tagish Lake meteorite.

Spectroscopic observations of small bodies have allowed the parent bodies of the main meteorite classes (ordinary chondrites (OCs), Howardite-Eucrite-Diogenites (HEDs), CM chondrites to name a few) to be identified and their distribution across the Solar System to be characterized (see [26] for a review). These observations have shown that the meteorite parent bodies are all located in the main asteroid belt (between 2 AU and 3.3 AU) and are absent beyond ~4 AU (Fig. 2). Such a distribution is compatible with a formation in the inner Solar System (< ~10 AU) for these bodies.

Telescopic observations of small bodies have further revealed that a large fraction (~50%) of the surface material of main-belt asteroids (at least 30% of all C-type asteroids and most P and D-types) as well as comets, Centaurs, and trans-Neptunian objects appear unsampled by our meteorite collections. Instead, interplanetary dust particles (IDPs) may be representative samples of the refractory surface material of these bodies [25, 26, 28, 50]. In particular, it is now well established that the water-rich Tagish Lake meteorite cannot be representative of the surface composition of D-type asteroids as suggested earlier [48]. Instead, the

Tagish Lake meteorite and possibly CI chondrites may be samples of the aqueously altered cores of these bodies [28]. Note that a definitive proof of this suggestion is currently missing.

3.2 Interplanetary dust particles: Only partially representative of primitive bodies

IDPs, the likely samples of the most primitive Solar System bodies, differ from meteorites in being much smaller (<2 mm), more plentiful (they contribute most of the mass of extra-terrestrial material that comes to the present-day Earth), and different in texture and composition [51]. In particular, some classes of IDPs appear to be the most primitive material in the Solar System and at present provide our best source of information on the nature and evolution of the particles in the preplanetary solar nebula [3, 52, 53]. IDPs are currently classified into two main classes (chondritic porous IDPs and phyllosilicate-rich IDPs; [51]) with chondritic porous IDPs (CP-IDPs) currently recognized among the available extra-terrestrial materials as the closest to the starting ones.

CP-IDPs are structurally similar to cometary materials in being extremely fine-grained, porous, and fragile [54, 55]. In fact, CP-IDPs are so fragile that these materials are unlikely to survive atmospheric entry as macroscopic bodies, so it is not surprising that similar materials are not represented in the meteorite collections. CP-IDPs are largely aggregates of subgrains <0.5 μm in diameter, with rare grains larger than several micrometers. The subgrains are solid nonporous matter containing a mix of submicrometer glass with embedded metal and sulfides (GEMS; [52]), organic materials, olivine, pyroxene, pyrrhotite, less-well-defined materials, and a number of less-abundant phases [51]. GEMS grains are submicrometer amorphous Mg-Si-Al-Fe silicate grains that contain numerous 10–50-nm-sized Fe-Ni metal and Fe-Ni sulfides, comprising up to 50 wt% of anhydrous IDPs. CP-IDPs are highly enriched in C [2–3× CI [56]] and volatile trace elements [57] relative to CI carbonaceous chondrites. Detailed chemical, mineralogical, and isotopic studies of these particles show that they have experienced minimal parent-body alteration (unlike CI and CM chondrites they escaped aqueous alteration), and are rich in presolar materials, e.g., presolar silicates [49].

One major difficulty with IDPs is to understand to what extent a given particle is representative of an entire body and to what extent its most fragile compounds have been lost or altered during its journey to Earth and/or during atmospheric entry. Using the texture of primitive meteorites such as type 3 ordinary chondrites or CV chondrites as a benchmark (Fig. 4) tells us that a 100 μm-sized IDP (this is the typical size of an IDP) cannot be representative by any means of a body at the 4-5 cm scale (which is the typical size of most recovered meteoritic samples) not to say of the bulk of its parent body. To sum up the difficulty of interpreting the IDP record, one should imagine all meteorites sieved into ~100 μm-sized fragments and subsequently mixed and dispersed. It would be impossible to retrieve the elemental, mineralogical, and isotopic composition of

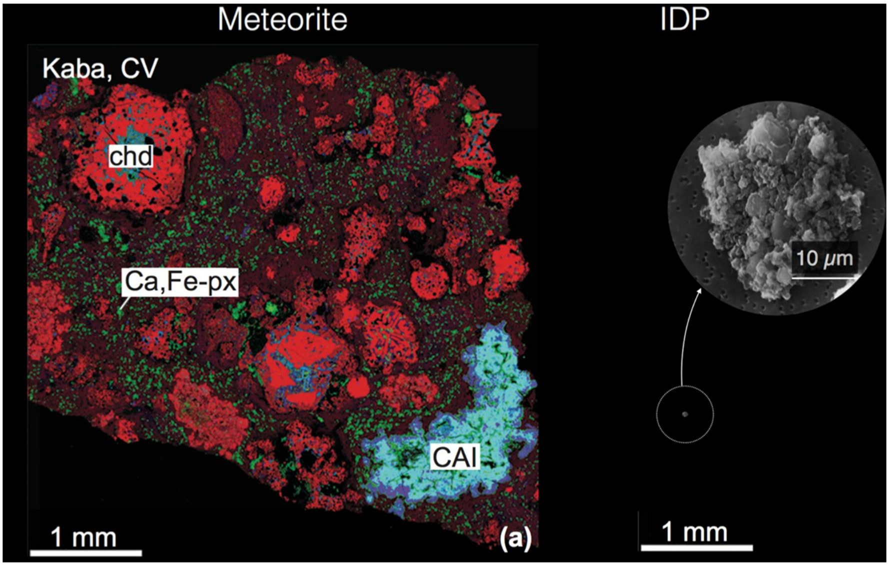

Fig. 4 Illustration of the sampling bias of IDP-like bodies with respect to meteorite-like ones based on current extra-terrestrial samples. Collected IDPs are far too small to be representative by any means of the overall composition of the body they originate from. Also, IDP-like bodies are volatile-rich and we crucially need to bring back intact volatiles from these objects to Earth to make progress in our understanding of their origin and composition. The IDP image is from Rietmeijer [58] and the meteorite chemical map is from Krot [59]

individual meteorite classes from this mixture. That is exactly the problem we are facing with IDPs.

IDPs also do not inform us about the composition of the volatiles present within their parent bodies. Yet, the low densities of IDP-like asteroids (see [26] for a review) and those of comets and KBOs imply that volatiles must be a main component of these bodies. Volatiles have been relatively well characterized in the case of comets [60] but without showing any particular trends or families amongst the comets. It remains to be determined whether the same volatiles are present in IDP-like asteroids, centaurs, and KBOs. The volatile composition may also vary from C- to P- to D-types informing us about a compositional trend in the protoplanetary disc.

In conclusion, although IDPs contribute most of the extra-terrestrial material that comes to the present-day Earth, their ultimate composition and their link with their parent population is far less understood than in the meteorite case. This stems from the fact that (i) the scientifically exploitable mass of material available to the science community is smaller by at least 12 orders of magnitude in the case of IDPs compared to meteorites, (ii) individual IDPs are not informative of the bulk composition of their parent body, and (iii) their parent bodies are not made of refractory material only but of volatiles as well (major fractions of volatiles obviously do not make it to the ground nor do they survive near-Earth temperatures).

4 The next step: Sample return of primitive matter from the outer Solar System

Reaching a global understanding of Solar System formation and evolution requires, inter alia, to possess representative samples from all major compositional classes of small bodies in our collections. So far, this is only the case for the parent bodies of meteorites, which represent less than 50% (in mass) of all Solar System small bodies (Fig. 3). Small bodies that appear unconnected to meteorites should therefore be targeted in priority. Among them, those that may be connected to CP-IDPs appear as the most promising targets for future exploration (see previous section). These comprise P- and D-type asteroids (both main-belt and near-Earth), Jupiter Trojans, comets, Centaurs, and small (D < 250 km) KBOs [25, 26, 28]. Note that both Ryugu and Bennu, targets of the Hayabusa 2 and OSIRIS-Rex missions, are C-type asteroids and thus less primitive than P/D types and comets (see Fig. 2).

The Nice model – which invokes a late outward migration of Uranus and Neptune [29–32] - implies that the P/D-type main-belt asteroids (and thus P/D near-Earth asteroids) and the Trojans of Jupiter likely have the same origin as outer Solar System small bodies such as Centaurs, short period comets, and small (D < 250 km) trans-Neptunian objects. Available spectroscopic observations of these populations as well as the similarity in size distributions between the Jupiter Trojans and trans-Neptunian objects (Fraser et al. 2014) support such an hypothesis (Fig. 5). It thus appears that both the near-Earth and main-belt asteroid population host a fraction of bodies that were formed in the outskirts of the young Solar System. In addition, an in-depth analysis of the spectral properties of these bodies along with numerical simulations that attempt to decipher their early thermal evolution imply that these objects have been barely affected by heating processes since their formation [22].

These objects (P/D type asteroids, Jupiter Trojans, comets, centaurs, small KBOs) - which seem to be genetically linked - thus appear as the most primitive known bodies in the Solar System. Based on current knowledge, they are the largest population of small bodies in the Solar System and they appear as the most likely parent bodies of CP-IDPs, which are so far the closest materials to the starting ones. The fact that the Tagish Lake meteorite and CP-IDPs, which have very different mineralogies and evolutionary histories, are likely from small bodies that formed in the outer Solar System underlines the importance for a careful selection of the target (see section 6). The lack of representative samples with CP-IDP composition in our collections of these primitive bodies implies that many major questions regarding the formation of these objects and that of the Solar System are still unanswered. We list them hereafter.

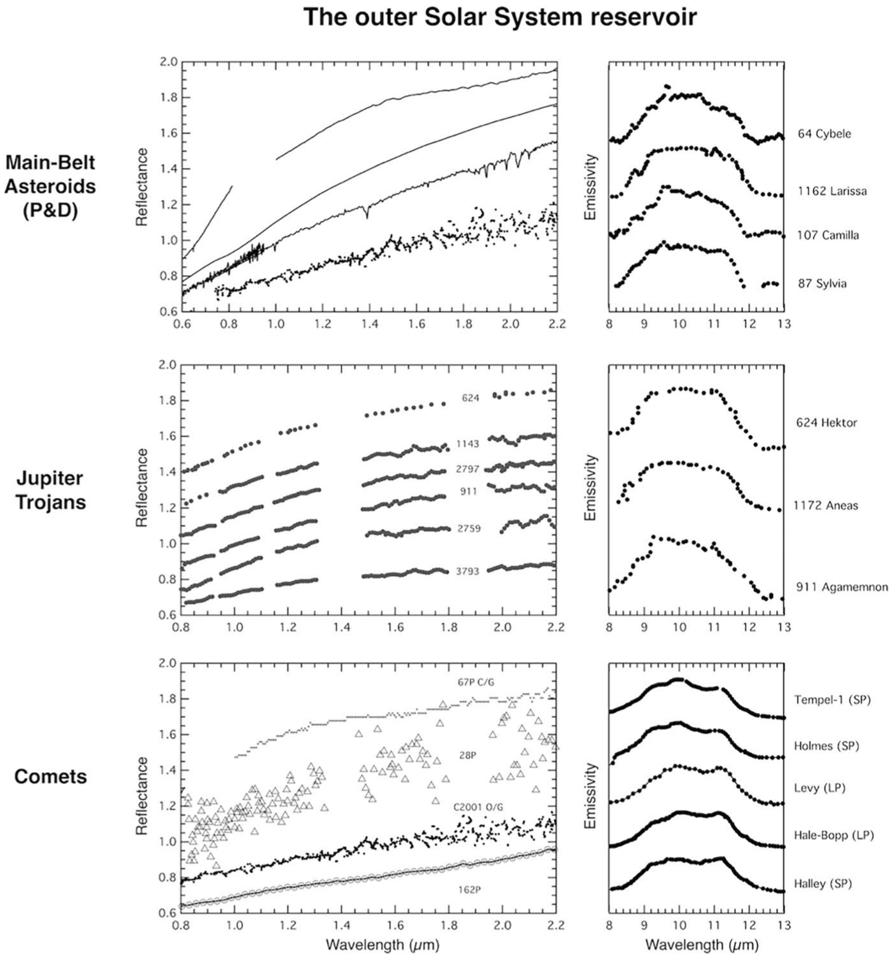

Fig. 5 Overview of the currently available spectral data over the near-infrared and mid-infrared spectral ranges for P/D-type main-belt asteroids, Jupiter Trojans, and comets suggesting a common origin for these now dynamically separated populations. Reprinted from Vernazza and Beck [26]

4.1 What is the path to an inhabited planetary system?

This is the founding interrogation of this White Paper. There are abundant astrophysical observations of the various stages of planet formation from the molecular clouds to protoplanetary discs to exoplanets. But they are snapshots at a given time, which often do not probe all chemical reservoirs, and only offer a partial view of the path to a planetary system. This proposal aims to understand the mechanisms from which a molecular cloud evolved into a planetary system. It is a case study, the Solar System, which happens to have evolved into an inhabited planetary system.

4.2 What were the initial ingredients of the Solar System and how were these ingredients distributed around the young sun?

4.2.1 What silicates?

Whereas silicate grains in the interstellar medium appear to be dominantly amorphous, current observations of P/D main-belt asteroids, Jupiter Trojans, and comets reveal a mixture of amorphous and crystalline silicates (Fig. 5). Furthermore, in all the aforementioned populations, there are objects enriched in crystalline olivine with respect to pyroxene whereas the remaining objects tend to have about as much crystalline pyroxene as olivine [25], thus implying two main primordial reservoirs of primitive small bodies as well as a compositional gradient in the primordial outer protoplanetary disc (10-40 AU).

Analyses in the laboratory of CP-IDPs (the probable analog materials of these bodies) reveal a similar mixture of amorphous and crystalline silicates. Nonetheless, the relative abundance of the two phases (amorphous vs crystalline) in primitive bodies remains an open question that these samples haven't addressed because of their small scale. Having representative samples of the outer Solar System will provide constraints on the exact nature/composition of the silicates and thus on the level and radial extent of thermal processing of the silicates in the protoplanetary disc.

4.2.2 What organics?

The nature and distribution of organic molecular material in the present-day Solar System is ultimately related to its origins, although dynamical interactions and processing have modified all but the most pristine. Diffuse interstellar and dense molecular clouds, of the kind that spawned the Sun and planets, contain copious quantities of the basic building blocks that led to ices and complex molecules of interest (e.g., [61, 62]). The early chemistry of our own Solar System and of other planetary systems is thought to depend, largely, upon the degree to which organic and ice components form (in the solid phase on dust grains or directly in the gas phase), are exchanged between the gas and solid state (as grains experience energetic processing), and survive in the developing planetary system (precursor and more complex materials).

So far, the question as to whether organics found in meteorites and IDPs have a Solar System origin or an ISM heritage has remained unanswered. Attempts to answer this question are hampered by poor sampling of Solar System organics. The Rosetta mission to comet 67P/Churyumov-Gerasimenko has emphasized the fact that some objects are extremely enriched in organics when compared to meteorites and IDPs (and inner Solar System objects). The estimated fraction of organic materials in cometary dust based on the Rosetta measurements is around 45 wt% [63, 64]. These results have raised the possibility that the outer Solar System is the host of “organic worlds”, while such organic-rich samples are extremely rare among the suite of cosmo-materials, and are limited to a few small dust particles (UCAMMs, [5]). Obtaining a sample of an outer Solar System small body would be key in addressing the nature and origin of extra-terrestrial organics.

4.2.3 What volatiles?

Comets are currently the most important source of knowledge regarding the nature and relative abundance of the volatiles that were incorporated in outer Solar System bodies.

More than 20 primary chemical species have now been detected in comets via spectroscopic surveys at infrared and radio wavelengths [60, 65] and in-situ observations by the Rosetta spacecraft [66, 67] including H_2O, CO, CO_2, CH_4, C_2H_2, C_2H_6, CH_3OH, H_2CO, $HOCH_2CH_2OH$, HCOOH, $HCOOCH_3$, CH_3CHO, NH_2CHO, NH_3, HCN, HNCO, CH_3CN, HC_3N, H_2S, OCS, SO_2, H2CS, and S_2 (see [66] for a more complete list). H_2O is the most abundant species followed by CO_2. Similar species have been observed in the interstellar medium (e.g., [68]).

In the Solar System, a fundamental question remains regarding the origin and early evolution of these volatiles. Specifically, to what degree is the volatile composition inherited from the parent molecular cloud, and to what degree are the volatiles formed in situ within chemically active regions in the disc, resetting previous chemical signatures and losing memory of the interstellar phase? Providing answers to this question would allow constraints to be placed on the thermodynamical profile of the outer protoplanetary disc during the early Solar System.

Another major unknown is the crystallographic structure of the ice species. Is it mainly amorphous or crystalline or a mixture of both? Also, are clathrates present? Answers to these questions would allow achieving a proper understanding of the trapping mechanisms of noble gases.

Finally, the source of Earth's water has been a matter of debate for decades: did water-rich asteroids or comets/TNOs deliver water to Earth? Some carbonaceous chondrites have been found to match the isotopic value (D/H) of Earth's oceans whereas the majority of comets have a higher D/H ratio ([69] and references therein). Yet, isotopic properties of water outgassed from cometary nuclei may be different due to fractionation effects at sublimation. In this case, all comets and by extension all objects formed in the outer Solar System may share the same Earth-like D/H ratio in water, with profound implications for the early Solar System and the origin of Earth's oceans [70].

4.2.4 Are there chondrules, CAIs, AOAs or other microstructures?

Chondrules, AOAs (Amoeboid Olivine Aggregates), and CAIs are ~mm-sized particles that record high-temperature processes and whose origin and formation process remains highly debated. It is currently proposed that AOAs and CAIs formed in the inner Solar System. Traces of these inclusions have been found in the Stardust samples of comet 81P/Wild 2. However, their overall abundance in primitive small bodies with respect to the remaining dust particles is currently unknown. Such information would provide valuable insights on the level of radial mixing in the Solar System accretion disc.

Moreover, we know via the current location of the chondrite (chondrule-rich meteorites) parent bodies (Fig. 2) that chondrule formation was an important process in the inner Solar System, but we do not know if this process occurred in the outer Solar System. Also, chondrule formation is expected to have been a motor of planetesimals formation (by pebble-accretion of self-gravitation, [71, 72]). If chondrules were essentially absent in the outer Solar System, what drove planetesimal formation there?

4.2.5 The radial compositional distribution around the young sun

One of the biggest unknowns regarding the composition of material around the young Sun is its radial distribution. We do not have direct evidence today on where the different classes of meteorites and IDPs formed in the protosolar nebula. The Stardust mission has revealed that some level of radial mixing occured [6] during the earliest epochs. However, there is growing evidence that poorly-mixed reservoirs existed in the early Solar System as shown by stable isotope systematics of non-carbonaceous and carbonaceous chondrites ([73, 74]; Fig. 6). One possible explanation for the observed isotopic dichotomy is the opening of a gap in the protosolar nebula generated by the formation of Jupiter [21]. In that case, it is expected that Saturn (and possibly Uranus and Neptune) should also have opened a gap raising the possibility for a further isotopic dichotomy between carbonaceous chondritic material and trans-Saturnian (not to say trans-Neptunian) material.

4.3 What is the fraction of presolar material that survived until today in outer Solar System bodies?

Outer Solar System objects are expected to host the most primitive Solar System materials and in particular materials that were not modified by early Solar System processes, and that formed through condensation in outer shells of presolar stars or by condensation in supernova ejectas: these are the presolar grains [12]. In the case

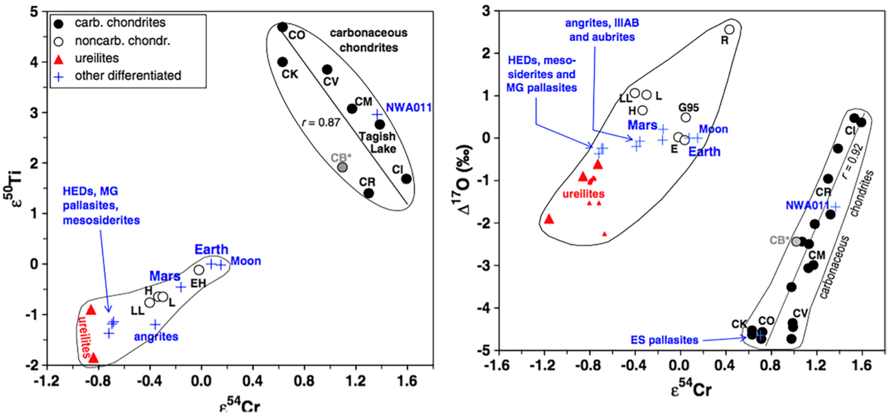

Fig. 6 (from [74]): Isotopic dichotomy between carbonaceous and non-carbonaceous meteorites. It is currently proposed that non-carbonaceous and carbonaceous meteorites formed inward and outward of Jupiter, respectively [21]. These types of measurements require ultra-high precision that can only be achieved in Earth's laboratories

of meteorites, such grains (SiC, graphite, silicates, …) that predate the formation of the Solar System have been identified through their exotic isotopic composition in major and minor elements (O, Mg, Si, Ti, C, N,…). These small grains are rare in available cosmomaterials and are the oldest materials we have in hand. Based on the detection of cosmogenic nuclides in presolar SiC grains, which were produced by spallation from galactic cosmic rays, exposure ages in interstellar space between 10 Myr and 1 Gyr were inferred [75, 76].

The abundance of presolar grains that were incorporated into outer Solar System objects is not known today. Their nature is also unconstrained. In the case of meteorites, only very refractory grains have been identified. This is likely related to the fact that inner Solar System materials experienced high-temperature processes or/and aqueous alteration. What we see today are the "survivors". It is very likely that outer Solar System objects contain a larger fraction of presolar grains, including types that could not have survived in the inner Solar System. Being able to study these grains would provide an unprecedented look at materials that were incorporated in the protosolar nebula. It is noteworthy in this respect that CP-IDPs contain on average about 2 times more presolar grains than the meteorites with the highest presolar grain abundances [49] and that individual IDPs associated with comet 26P/Grigg-Skjellerup were observed to have presolar grain concentrations of up to 1.5 wt% [77], reaching the estimated abundance of a few percent of stardust in the presolar molecular cloud [13].

4.4 How diverse was the origin of the starting materials and what was the environment of the protosolar nebula and pre-solar cloud core?

The astrophysical environment of Solar System formation can be studied by looking at the structure of the constituents of the protosolar nebula. Having access to such materials is key to probe the astrophysical environment of the protosolar nebula and the pre-solar cloud core. This can only be achieved through measurements in Earth-based laboratories. This includes the presence of short-lived radio-nuclides (e.g., ^{10}Be, ^{26}Al, ^{36}Cl, ^{41}Ca, ^{53}Mn, ^{60}Fe) which can form through distinct processes (injection from a late SN, continuous production in the Galaxy, irradiation in the early Solar System) to probe the few Myr before and after Solar System time 0 (time of CAI inclusion). This also includes measurements of spallation products (^{6}Li for example) or cosmogenic isotopes of rare gases to probe the irradiation history of presolar grains as they travelled through the ISM.

4.5 What is the pathway of life-forming elements (C,H,N,O, S) from the interstellar medium to the Solar System?

Life forming elements (C,H,N,O,S) are amongst the most abundant in the Solar System. However, understanding the conditions for the emergence of life requires to have a full understanding of the chemical form in which these elements were delivered to

Earth, and the chronology of the delivery (initial accretion, late accretion, Nice Model). It is noteworthy that there is a highly active debate regarding the origin of extra-terrestrial organic compounds. Some authors favour a direct heritage from the interstellar medium, whereas others argue for a Solar System origin, whether as gas phase chemical products in the earliest phases, or as a product of water-rock interaction on the parent body.

Most of these elements are often considered to be volatiles. Indeed, they can be found as molecules or ices in the interstellar medium. But they can also occur in much more refractory states: complex refractory organic molecules (C,H,N,O,S), carbides (C), nitrides (N), oxides (O), as well as sulfides (S). This means that following the pathway of life-forming elements from the ISM to the Solar System requires characterizing both the volatiles and the refractory phase including the relative abundance of the two, and the distribution of each element across each reservoir. Having samples of both the ice and mineral constituents of objects that formed in the outer Solar System would provide new groundbreaking knowledge on the carriers and origin of life-forming elements. The carriers of these elements could be assessed through a combination of mineralogy and organic chemistry, and the steps involved in the formation process could be investigated in the laboratory through elemental and isotopic measurements.

4.6 How and when did planetesimals accrete in the outer Solar System?

With definitive proof of the existence of the extinct short-lived nuclide ^{26}Al in the Solar System [78] came the realization that the major heat source for smaller bodies must have been from the decay of ^{26}Al as suggested earlier by Urey [79]. Internal evolution models generally assume an accreted abundance of ^{26}Al tied to the time of formation of the calcium–aluminum inclusions (CAIs) and that ^{26}Al was distributed uniformly throughout the Solar System. Under these assumptions, chronologies of the formation timescales of the main compositional classes of the Solar System have been established ([22] and references therein). It appears that primitive small bodies (comets, P/D main-belt asteroids, and small TNOs) must have formed at least 5 Myrs after CAIs [22] and that they were the last generation of small bodies to form.

The level of heterogeneity of ^{26}Al concentrations is, however, debated in the cosmochemical literature (e.g., [80–82]). It has been suggested that ^{26}Al was injected into the Solar System from an external, proximal supernova source (e.g. [83]), allowing for heterogeneity due to incomplete mixing. Alternatively, it was pointed out that the Solar System's complement of ^{26}Al is normal for massive star-forming regions in general [84, 85], suggesting a homogeneous distribution inherited from the parental molecular cloud.

Characterizing the concentration of ^{26}Al in samples of primitive bodies is therefore of prime importance to establish the chronology of events in the early Solar System and to understand whether these bodies are primitive because they accreted late or because ^{26}Al was initially absent.

5 The era of sample return

Recent observations of asteroid (4) Vesta with VLT/SPHERE [86] and of Neptune with VLT/MUSE (https://www.eso.org/public/images/eso1824a/) have revealed in a striking fashion to what extent the gap between interplanetary missions and ground-based observations is getting narrower. With the advent of very large telescopes (ELT, GMT, TMT), the science objectives of future interplanetary missions have to be carefully thought out so that these missions will complement – not duplicate – what will be achieved via Earth-based telescopic observations in the next decades.

For instance, future ELT adaptive-optics imaging observations of main-belt asteroids will allow us to resolve craters down to ~2-5 km in size implying that we will be able to characterize their geological history from the ground. In a different register, ELT and JWST observations of Jupiter with the near-infrared integral field spectrograph HARMONI (ELT) and NIRSpec (JWST), respectively, will have a higher spatial resolution (at least a factor of 3) than those performed in-situ by the ESA JUICE mission with the MAJIS near-infrared imaging spectrometer. In the field of Solar System small bodies, this propels missions performing cosmochemistry, namely sample return missions and to a lesser extent landing missions, at the forefront of space exploration.

Also, a sample return mission has formidable advantages over other missions as the samples are available for scientific measurements for "eternity" implying that future generation instruments will be able to re-analyse the samples as it is routinely the case with meteorites or Lunar samples and thereby allow making new discoveries over time.

6 Mission profile and instruments

Our top-level science questions require a sample return mission of a small body whose surface composition is as primitive as possible. By primitive, we imply that the surface should not have witnessed any major alteration process including aqueous alteration, metamorphism, and differentiation. The surface/subsurface should be volatile-rich and the refractory phase should be similar to CP-IDPs. Currently, P/D asteroids, comets, Jupiter and Neptune Trojans, Centaurs, and small ($D < 250$ km) TNOs appear as suitable targets as their refractory phase is similar to CP-IDPs. Among these populations, P/D asteroids and comets are being favored as they are the most accessible targets. Between these two populations (comets and P/D asteroids), comets are probably the most primitive bodies. The presence of volatiles at the surface and/or within the subsurface of P/D asteroids is not guaranteed, especially in the case of P/D near-Earth asteroids. One task during the study phase of the mission will be to properly evaluate whether near-Earth asteroids (NEAs) are meaningful targets for such a mission. Results from the OSIRIS-REx and Hayabusa 2 sample return missions will be key in this respect. A strawman mission concept is described below starting first with the instrument payload of both the main spacecraft and of an eventual lander, then the mission profile, and finally the sample return capability.

6.1 Instrument payload description for main spacecraft

6.1.1 Orbital payload

The top drivers of the payload strategy are to enable a safe sampling of the surface, and to maximize the scientific value of returned samples by providing a detailed geological and chemical context of the returned samples. It will essentially provide the surface composition in terms of mineralogy and volatiles abundances, as well as the physical properties of the surface (roughness, thermal inertia, surface temperature).

Optical camera This instrument would meet both engineering and scientific requirements (e.g., [87]). Visible camera observations are needed for spacecraft navigation purposes, for the reconstruction of the shape of the small body with the stereo-photogrammetry technique, for selecting sampling areas, and for geological studies. To achieve both global coverage and high spatial resolution two camera systems could be considered: a wide-angle camera and a narrow angle camera. In order to map physical or compositional variations across the surface, the cameras could be equipped with color filters. Color observations would be key to link in situ measurements with the visible-range spectra acquired by Earth-based telescopes.

Near and thermal infrared imaging spectrometers Previous ESA missions have demonstrated how these instruments are key for characterizing planetary bodies in terms of mineralogy and physical properties (e.g., [88]). Absorption bands in the near-infrared range (1-7 µm) are diagnostic of mineral and volatile species and can be detected with spectrometers using current technologies. Knowledge of the surface mineralogy and organics is key in reconstructing the conditions during the origin and evolution of the small body. Spectral observations in the thermal infrared range (~7-100 µm) can be used to detect complementary minerals as well as to measure surface brightness temperature and derive surface thermal inertia. The latter property is key in retrieving the grain size distribution (granulometry), thermal conductivity, porosity, and density of surface materials. Characterizing well these properties across the surface is key for determining the most favourable sites for sample collection. Should the targeted body potentially host permanently shadowed regions, observations in the far infrared range could be considered to study surface deposits at low (<50 K) temperatures.

Mass spectrometer In the case of an outgassing target (e.g., comet), a mass spectrometer (e.g., [89]) should be part of the payload to characterize the nature and relative abundance of the different volatile species (H_2O, CO, CO_2, etc..) including noble gases (Ne, Ar, Kr, Xe) and their main isotopes. Furthermore, on the way back to Earth, the mass spectrometer can be used to monitor highly volatile species sublimating from the collected target.

Radar ranger and close sub-surface imager Volatiles are not expected at the surface of main-belt asteroids or near-Earth asteroids, but could be present in the close sub-surface as was observed on Ceres [90]. A neutron spectrometer would not provide sufficient spatial resolution to investigate the distribution of volatiles on a small object, but the presence of layers of volatiles could be assessed with high-frequency radar. This instrument could also serve as an altimeter to support the descent and sampling phases.

Radio science experiment A *radio science experiment* (e.g., [91]) monitors the motion of the spacecraft using radio-tracking data in order to derive, in combination with camera and laser altimeter data, a set of properties of the body, such as mass, center of mass, the gravity field, rotation axis, and moments of inertia. Starting from these properties, the interior structure and distribution of mass within the object can be modelled.

6.1.2 Surface payload

Landing a lander/rover at the surface to precisely determine the nature and origin of the local context would definitely be a plus. In the case where the spacecraft could host a ~ 50 kg lander (including payload), such an option should be considered seriously as it would allow several key measurements to be performed at the surface. The costs of the lander could be covered - similarly to the instruments - by the ESA member states. Typically, the lander/rover payload could include: an Alpha Proton X-ray Spectrometer (APXS) to determine the chemical composition; an ion laser mass analyzer to perform molecular, isotopic, and elemental analysis of the surface for geochemical characterization; one or several gas analyzers to determine the elemental, molecular and isotopic composition of ices; a thermogravimeter to monitor the possible cometary activity and measure the volatile content in the regolith; a set of sensors to measure the mechanical, thermal, electrical, and acoustic surface and subsurface properties; and a panoramic, close-up, and microscopic imaging system. Additional lander payload could include a drill, a mid-infrared spectrometer, and a Raman microscope, for ices and organics.

Considerable expertise and heritage exist within Europe for both the main spacecraft and lander/rover instruments. In the case of the lander/rover, the proposed mission will capitalize and valorize the considerable investment put in the Philae Lander of the Rosetta mission, in the MASCOT lander onboard Hayabusa 2, and in the ExoMars rover (e.g., [92]). New developments to improve performances and miniaturization are expected in the coming years in the framework of new missions.

6.2 Baseline Mission architecture

A sample return mission to a small body requires the following functions: interplanetary outbound and inbound transfer, small body orbiting, descent-sampling-reascent phases, and Earth re-entry. The necessity to sample multiple locations can be addressed by multiple descent and sampling phases at different locations or by hopping across the surface. Either a single spacecraft or a configuration with a mother spacecraft and a landing/hopping platform could be envisaged. The design of the descent, touchdown, and sampling strategy can nowadays take advantage of the expertise gained by precursor JAXA and NASA missions. Particular importance should be given to the type of terrain that the surface platform and sampling mechanism can encounter. Recent missions have shown that terrains can vary considerably from a smooth regolith surface to a very rough landscape, and a flexible system should be designed.

6.3 Sample return key capability

We have identified three key capabilities that a future mission needs to have in order to meet the science objectives.

1) Sample, preserve, and return material at cryogenic temperatures in order to keep volatiles species, i.e., water ice, in their solid form. The temperature of liquid nitrogen (77 K) is sufficient to preserve both crystalline and amorphous ice over a mission time of 5 years. This capability is needed for any volatile and organic bearing targets, like asteroids, and is not limited to comet nuclei. To keep other volatiles such as CO and CO_2 and to retain heavy noble gases, a lower temperature (down to 10 K) would be required.
2) Sample multiple locations on the target. Lessons from previous space missions have shown that small bodies are chemically, mineralogically, and geologically heterogeneous, either due to their formation or evolution. The selection of the sampling locations should be driven by a detailed remote-sensing reconnaissance of the target in a phase prior to sampling.
3) Sampling multiple lithologies, including loose regolith (if present), rootless pebble or rock, and a drill core. Obtaining a core down to around ten cm may allow us to probe below the thermal skin of the object and sample volatile rich material. It will also enable us to study the effects of space weathering processes by micrometeoroids bombardments, as well as solar radiation induced fracturing and chemical processing of surface material.

6.4 Flexibility in the choice of the target

The great flexibility in the choice of the target (e.g., P-type main-belt asteroid, D-type main-belt asteroid, olivine-rich comets, comets enriched in pyroxene, Oort cloud comet entering the inner Solar System for the first time; [25]) implies that there is space for several sample return missions to primitive bodies to probe the diversity of this population. Note that the target should be chosen among small bodies that have been spectroscopically well characterized over an extended wavelength range to definitively ensure a high degree of similarity between the latter and CP-IDPs. Over a limited wavelength range (e.g., visible range alone), the compositional interpretation is rarely unique opening the possibility for an erroneous selection.

7 Conclusion

The last thirty years of cosmochemistry and planetary science have shown that one major Solar System reservoir is vastly undersampled in the available suite of extra-terrestrial materials, namely small bodies that formed in the outer Solar System (>10 AU). This reservoir is of tremendous interest, as it is recognized as the least processed since the dawn of the Solar System and thus the closest to the starting materials from which the Solar System formed. Some of the next major breakthroughs in planetary science will come from studying outer Solar System samples (volatiles and refractory constituents) in the laboratory. Yet, this can only be achieved by an L-class mission that directly collects and returns to Earth materials from this reservoir. The selected target should be as primitive as possible. Comets and P/D main-belt asteroids including main-belt comets would then appear as the most accessible and scientifically valuable targets, with comets being our preferred targets because of their activity that can be used to characterize the volatiles and also because their surface should be more "primitive" due to the involved erosion processes.

Funding Open Access funding enabled and organized by Projekt DEAL.

References

1. Messenger et al.: Meteorites and the Early Solar System II, D. S. Lauretta and H. Y. McSween Jr. (eds.), University of Arizona Press, Tucson, 187-208 (2006)
2. Hoppe et al.: Space Sci. Rev. **214**, 106 (2018)
3. Flynn et al.: Elements **12**, 177-183 (2016)
4. Ishii et al.: Science **319**, 447 (2008)
5. Duprat et al.: Science **328**, 742 (2010)
6. Brownlee et al.: Science **314**, 1711 (2006)
7. Pfalzner et al.: Physica 90 (2015)
8. Amelin et al.: Science **297**, 1678-1683 (2002)
9. Amelin et al.: Earth Planet. Sci. Lett. **300**, 343-350 (2010)

10. Bouvier et al.: Geochim. Cosmochim. Acta **71**, 1583-1604 (2007)
11. Zhukovska et al.: Astrophys. J. **831**, 147 (2016)
12. Zinner.: In: Meteorites and Cosmochemical Processes, ed. A. M. Davis Elsevier, Amsterdam, 181 (2014)
13. Hoppe et al.: Nat. Astron. **1**, 617 (2017)
14. Kemper et al.: Astrophys. J. **609**, 826-837 (2004)
15. Pendleton et al.: Astrophys. J. **437**, 683 (1994)
16. Sandford et al.: Astrophys. J. **371**, 607 (1991)
17. Lisse et al.: Science **313**, 635-640 (2006)
18. Nakamura et al.: Science **321**, 1664-1667 (2008)
19. Zolensky et al.: Science **314**, 1735-1739 (2006)
20. Ciesla.: Science **318**, 613 (2007)
21. Kruijer et al.: Proc. Natl. Acad. Sci. **114**, 6712-6716 (2017)
22. Neveu & Vernazza.: Astrophys J. 875 (2019)
23. Henke et al.: A&A **545**, A135 (2012)
24. Monnereau et al.: Geochim. Cosmochim. Acta **119**, 302-321 (2013)
25. Vernazza et al.: Astrophys. J. **806**, 204 (2015)
26. Vernazza & Beck.: Planetesimals: Early Differentiation and Consequences for Planets, ed. L. T. Elkins-Tanton & B. P. Weiss. Cambridge Univ. Press, Cambridge, 269 (2017)
27. Fujiya et al.: Nat. Astron. (2019)
28. Vernazza et al.: Astron. J. **153**, 72 (2017)
29. Gomes et al.: Nature **435**, 466-469 (2005)
30. Levison et al.: Nature **460**, 364-366 (2009)
31. Morbidelli et al.: Nature **435**, 462-465 (2005)
32. Tsiganis et al.: Nature **435**, 459-461 (2005)
33. Walsh et al.: Nature **475**, 206-209 (2011)
34. Bland et al.: Nat. Commun. **5**, 5451 (2014)
35. Brearley.: Meteorites and the Early Solar System II, D. S. Lauretta and H. Y. McSween Jr. (eds.), University of Arizona Press, Tucson, 943, 584-624 (2006)
36. Davison et al.: Astrophys. J. **821**, 68 (2016)
37. Grimm & McSween.: Science **259**, 653-655 (1993)
38. Beck et al.: Icarus **229**, 263-277 (2014a)
39. Beck et al.: Meteorit. Planet. Sci. **49**, 2064-2073 (2014b)
40. Bonal et al.: Geochim. Cosmochim. Acta **189**, 312-337 (2016)
41. Garenne et al.: Icarus **264**, 172-183 (2016)
42. Bischoff et al.: In: Lauretta, D.S. (Ed.), Meteorites and the Early Solar System II. 679–712 (2006)
43. Lentfort et al.: Meteorit. Planet. Sci. **56**, 127-147 (2021)
44. Morlok et al.: Geochim. Cosmochim. Acta **70**, 5371-5394 (2006)
45. Bischoff et al.: Geochim. Cosmochim. Acta **293**, 142-186 (2021)
46. Bischoff et al.: Earth Planet. Sci. Lett. **66**, 1-10 (1983)
47. Kieffer.: Moon **13**, 301-320 (1975)
48. Hiroi et al.: Science **293**, 2234 (2001)
49. Floss & Haenecour.: Geochemical. J. **50**, 3 (2016)
50. Bradley et al.: Meteorit. Planet. Sci. **31**, 394-402 (1996)
51. Bradley.: Meteorites, Comets and Planets: Treatise on Geochemistry 1. Edited by A. M. Davis. Executive Editors: H. D. Holland and K. K. Turekian. Amsterdam, The Netherlands, 689 (2005)
52. Bradley.: Formation and Evolution of Solids in Space. In: J. Mayo Greenberg and Aigen Li (eds.). Kluwer Academic Publishers, pp. 485-503 (1999)
53. Levasseur-Regourd et al.: Space Sci. Rev. **214**, 64 (2018)
54. Bradley & Brownlee. Science **231**, 1542-1544 (1986)
55. Rietmeijer & McKinnon.: Nature **326**, 162-165 (1987)
56. Thomas et al.: Geochim. Cosmochim. Acta **57**, 1551-1566 (1993)
57. Flynn et al.: Meteoritics **28**, 349 (1993)
58. Rietmeijer.: Adv. Space Res. **39**, 583-589 (2007)
59. Krot.: Meteorit. Planet. Sci. **54**, 1647-1691 (2019)
60. Mumma & Charnley.: Annu. Rev. Astron. Astrophys. **49**, 471-524 (2011)
61. Boogert et al.: Annu. Rev. Astron. Astrophys. **53**, 541-581 (2015)
62. Pendleton & Allamandola.: Astrophys. J. Suppl. Ser. **138**, 75-98 (2002)

63. Bardyn et al.: MNRAS **469**, 712-722 (2017)
64. Herique et al.: Mon. Not. R. Astron. Soc. **462**, 516-532 (2017)
65. Bockelee-Morvan et al.: In Comets II, p. 391 (2004)
66. Altwegg et al.: Ann. Rev. Astron. Astrophys. **57** (2019)
67. Le Roy et al.: Astron. Astrophys. **583**, A1 (2015)
68. Gibb et al.: Astrophys. J. Suppl. Ser. **151**, 35-73 (2004)
69. Altwegg et al.: Science 347 (2015)
70. Lis et al.: Astron. Astrophys. 625 (2019)
71. Alexander et al.: Science **320**, 1617 (2008)
72. Johansen et al.: Asteroids IV, Patrick Michel, Francesca E. DeMeo, and William F. Bottke (eds.), University of Arizona Press, Tucson, 471-492 (2015)
73. Budde et al.: Earth Planet. Sci. Lett. **454**, 293-303 (2016)
74. Warren.: Earth Planet. Sci. Lett. **311**, 93-100 (2011)
75. Gyngard et al.: Publ. Astron. Soc. Aust. **26**, 278-283 (2009)
76. Heck et al.: Astrophys. J. **698**, 1155-1164 (2009)
77. Busemann et al.: Earth Planet. Sci. Lett. **288**, 44-57 (2009)
78. Lee et al.: Astrophys. J. **211**, 107-110 (1977)
79. Urey.: Proc. Natl. Acad. Sci. **41**, 127 (1955)
80. Krot et al.: Meteorit. Planet. Sci. **47**, 1948–1979 (2012)
81. Makide et al.: Geochim. Cosmochim. Acta **110**, 190–215 (2012)
82. Van Kooten et al.: Proc. Natl. Acad. Sci. **113**, 2011-2016 (2016)
83. Ouellette et al.: Astrophys. J. **662**, 1268-1281 (2007)
84. Jura et al.: Astrophys. J. Lett. **775**, L41 (2013)
85. Young.: Earth Planet. Sci. Lett. **392**, 16027 (2014)
86. Fetick et al.: Astron. Astrophys. **623**, ID. A6 (2019)
87. Keller et al.: Space Sci. Rev. **128**, 433-506 (2007)
88. Coradini et al.: Space Sci. Rev. **128**, 529-559 (2007)
89. Balsiger et al.: Space Sci. Rev. **128**, 745-801 (2007)
90. Prettyman et al.: Science **355**, 55-59 (2017)
91. Paetzold et al.: Space Sci. Rev. **128**, 599-627 (2007)
92. Vago et al.: Astrobiology, **17**, 471-510 (2017)
93. Kueppers et al.: Exp. Astron. 23, **3**, 809-847 (2008)

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Authors and Affiliations

P. Vernazza[1] · P. Beck[2] · O. Ruesch[3] · A. Bischoff[3] · L. Bonal[2] · G. Brennecka[4] · R. Brunetto[5] · H. Busemann[6] · J. Carter[1,5] · C. Carli[7] · C. Cartier[8] · M. Ciarniello[7] · V. Debaille[9] · A. Delsanti[1] · L. D'Hendecourt[10] · E. Füri[8] · O. Groussin[1] · A. Guilbert-Lepoutre[11] · J. Helbert[12] · P. Hoppe[13] · E. Jehin[14] · L. Jorda[1] · A. King[15] · T. Kleine[3] · P. Lamy[16] · J. Lasue[17] · C. Le Guillou[18] · H. Leroux[18] · I. Leya[19] · T. Magna[20] · Y. Marrocchi[8] · A. Morlok[3] · O. Mousis[1] · E. Palomba[7] · L. Piani[8] · E. Quirico[2] · L. Remusat[21] · M. Roskosz[21] · M. Rubin[19] · S. Russell[15] · M. Schönbächler[6] · N. Thomas[19] · J. Villeneuve[8] · V. Vinogradoff[10] · P. Wurz[19] · B. Zanda[21]

✉ P. Vernazza
pierre.vernazza@lam.fr

✉ O. Ruesch
ottaviano.ruesch@uni-muenster.de

[1] Aix Marseille Université, CNRS, CNES, Laboratoire d'Astrophysique de Marseille, Marseille, France

[2] Université Grenoble Alpes, CNRS, Institut de Planétologie et d'Astrophysique de Grenoble, Grenoble, France

[3] Institut für Planetologie, University of Münster, Münster, Germany

[4] Lawrence Livermore National Laboratory in Livermore, Livermore, CA, USA

[5] Université Paris-Saclay, CNRS, Institut d'Astrophysique Spatiale, Bures-sur-Yvette, France

[6] Institute of Geochemistry and Petrology, ETH Zürich, Zürich, Switzerland

[7] Istituto di Astrofisica e Planetologia Spaziali, Istituto Nazionale di Astrofisica (INAF), Rome, Italy

[8] CRPG, CNRS, Université de Lorraine, UMR 7358, Vandœuvre-lès-Nancy, France

[9] Laboratoire G-Time, Université Libre de Bruxelles, Bruxelles, Belgium

[10] Aix-Marseille Université, CNRS, PIIM, Marseille, France

[11] LGL-TPE, UMR5276 CNRS/ENS/Université Claude Bernard Lyon 1, Villeurbanne, France

[12] Institute for Planetary Research, German Aerospace Center DLR, Berlin, Germany

[13] Max Planck Institute for Chemistry, Particle Chemistry Department, Mainz, Germany

[14] Space sciences, Technologies and Astrophysics Research Institute, Université de Liège, Liège, Belgium

[15] Department of Earth Sciences, The Natural History Museum, London, UK

[16] Laboratoire Atmosphères, Milieux et Observations Spatiales, CNRS, Université de Versailles Saint-Quentin-en-Yvelines, Versailles, France

[17] IRAP, Université de Toulouse, CNES, CNRS, UPS, Toulouse, France

[18] Univ. Lille, CNRS, INRA, ENSCL, Unité Matériaux et Transformations, Lille, France

[19] Physics Institute, University of Bern, Sidlerstrasse 5, 3012 Bern, Switzerland

[20] Czech Geological Survey, Klárov 3, CZ-118 21 Prague 1, Czech Republic

[21] Muséum National d'Histoire Naturelle, CNRS, Sorbonne Université, Institut de Minéralogie, Physique des Matériaux et Cosmochimie, IMPMC, Paris, France