SAMPLE OF HIGH-PRIORITY SCIENCE OBJECTIVES FOR FUTURE INTERPLANETARY MISSIONS TOWARDS ASTEROIDS

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Abstract. In this paper, we present a sample of high-priority science objectives for future interplanetary missions towards asteroids that were submitted to ESA as a white paper in 2013.

Key words: asteroids – interplanetary exploration – space missions.

1. THE ASTEROID BELT: WHY IS IT SUCH AN INTERESTING PLACE FOR FUTURE INTERPLANETARY EXPLORATION?

Our present knowledge of the asteroid belt, a population of $\sim 10^6$ small bodies larger than 1km in orbit between Mars and Jupiter, is mostly based on i) ground-based observations, ii) dynamical simulations, iii) meteorite measurements, and to a lesser extent, on in-situ observations by space missions as only 9 main belt asteroids have been visited by a spacecraft (7 flybys and only 2 rendezvous).

Spectroscopy in the visible and near-infrared range (VNIR, 0.4–2.5 μm) has proven to be a powerful tool for constraining the surface composition of solar system bodies, asteroids in particular. As of today, more than 2000 main belt asteroids (Bus & Binzel, 2002) have been observed via visible spectroscopy (0.4–0.9 μm) whereas a few hundred objects have been observed in the near-infrared (0.9–2.5 μm). Their spectral properties in the combined VNIR range (0.4–2.5 μm) indicate the presence of an incredible number of compositional groups (24, as presented in Figure 1). No other population of small bodies in our solar system exhibits such compositional diversity. Only two compositional groups have been identified among Jupiter Trojans (Emery *et al.*, 2011), Trans-Neptunian Objects (TNOs) seem to comprise four to five compositional groups only and most of the giant planet' satellites seem to be very similar in composition (water-rich surfaces).

When looking at the composition of asteroids and its distribution across the

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main belt, there are three fundamental properties that directly constrain the formation and evolution of the main belt:

i) There are two main asteroid populations, the so-called S-types (ordinary chondrite-like asteroids) and C-types (carbonaceous chondrite-like asteroids) accounting for more than 50% of all main belt asteroids and several minor populations (Figures 1 and 2). They comprise the parent bodies of the remaining known meteorite classes but also bodies whose composition is not represented in our meteorite collections bringing the total number of spectral classes to 24 according to the latest taxonomy proposed by DeMeo *et al.* (2009). No other population of small bodies in our solar system exhibits such a compositional diversity. Indeed, only two compositional groups have been identified among Jupiter Trojans (Emery *et al.*, 2011), four to five among TNOs (Barucci *et al.*, 2005), and most of the giant planet' satellites seem to be very similar in composition (water-rich surfaces);

ii) A heliocentric gradient with water-poor S- type asteroids being preferentially located in the inner belt whereas water-rich C-types are the dominant population in the outer belt (Figure 1 in Gradie and Tedesco, 1982);

iii) A compositional overlap where both C- and S-types co-exist in the heliocentric region from 2.3 to 3.2 AU (Figure 1).

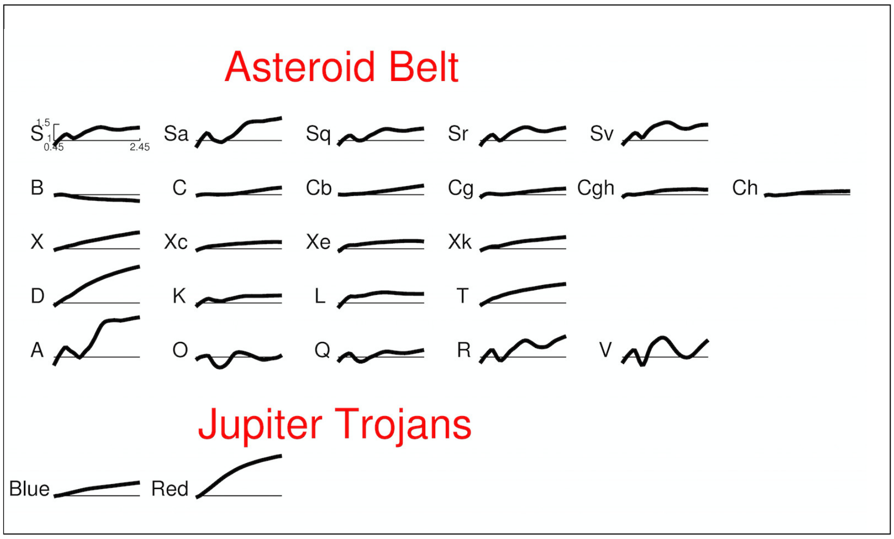

Fig. 1 – Compositional diversity of the asteroid belt illustrated by its spectral reflectivity in the VNIR domain. There are 24 spectral classes within the Main Belt and only two spectral classes among Jupiter Trojans.

These three properties have been used as key tracers of the early dynamical evolution of the solar system. Bottke *et al.* (2006) proposed that a small population of planetesimals that formed in the terrestrial planet region has been scattered into the main belt by emerging protoplanets early in its history, thus predicting that some main belt asteroids are interlopers. Later, Levison *et al.* (2009) showed that the violent dynamical evolution of the giant-planet orbits required by the so-called Nice model (Gomes *et al.*, 2005; Tsiganis *et al.*, 2005; Morbidelli *et al.*, 2005) which took place 700 Myrs after solar system formation led to the insertion of primitive trans-neptunian objects into the outer belt. Both these models help explaining the first property, namely the presence of several minor populations in the asteroid belt. Recently, a new dynamical scenario proposed by Walsh *et al.* (2011) and invoking an early inward migration of Jupiter and Saturn to 1.5 AU in order to explain Mars' low mass - shows that the asteroid belt region may comprise bodies formed in the inner (1-3 AU) as well as the outer (4-13 AU) regions of the solar system. In particular, their scenario helps explaining the second and third properties: the S- and C-types formed on each side of the snowline[*] ($\leq$3 AU for S-types; $\geq$4 AU for C-types), explaining why S-types are water-free while C-types are water-rich. It further explains why S- and C-types overlap in heliocentric distance as a natural outcome of their respective migrations to their current locations.

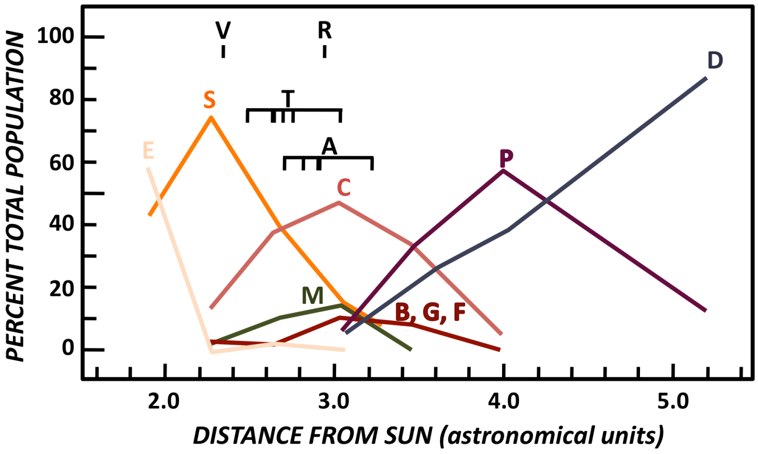

Fig. 2 – Compositional gradient within the asteroid belt (Gradie and Tedesco, 1982).

[*] The snowline corresponds to the inner boundary of the water ice condensing region: beyond this limit, the solar nebula was cool enough so that volatiles condensed in icy grains, which were then accreted into planetesimals. This process occurs at a temperature in the range from 145 to 170 K depending on the partial pressure of water vapor. In the optically thin solar nebula, the snowline is estimated to be located at 2.7 AU.

All in all, the idea of a static solar system history has dramatically shifted to one of dynamic change and mixing (DeMeo & Carry, 2014). In a broad stroke, the idea that the asteroid belt is a condensed version of the primordial solar system is progressively emerging. The asteroid belt (*i.e.*, the Earth's neighbourhood) therefore appears an ideal place for testing solar system formation models and for exploring the building blocks predicted by models of i) the telluric planets, ii) the giant planet cores, iii) the giant planets' satellites, and iv) outer small bodies such as TNOs and comets. It also appears as an ideal place to search for the origin of Earth's water.

Whereas reaching a full comprehension of the solar system formation and evolution eventually requires collecting detailed constraints of the physical properties of all populations of small bodies, it therefore appears that the diversity of the main belt asteroids offers a first, simple approach to this global investigation. A large fraction of these constraints can certainly be inferred from both ground- based observations and meteorite measurements, but several key constraints require in situ measurements which, in the foreseeable future, are only reachable for relatively close objects.

In 2013, a collective brainstorming exercise between ground and space observers, meteoricists and dynamicists on the future in-situ measurements that would not only lead to significant breakthroughs but also deliver constraints that cannot be obtained from Earth neither today nor in the foreseeable future identified the following top level science objectives that justify new interplanetary missions:
1) The exploration of the diversity of the asteroid belt;
2) The first investigation of the internal structure of asteroids;
3) The origin of water on Earth.

The sections below consider in detail these three science themes.

2. THE EXPLORATION OF THE DIVERSITY OF THE ASTEROID BELT

Up to now, only six asteroid types out of the identified 24 types (DeMeo *et al.*'s classification) have been observed at close range by space mission: six S- types (Gaspra, Ida, Annefrank, and Toutatis *via* flybys, Itokawa and Eros *via* rendezvous), one V-type (Vesta *via* rendezvous), one Xe-type (Steins *via* flyby), one Xc- type (Lutetia *via* flyby), one C-type (Ceres) and one Cb-type (Mathilde *via* flyby). Two other S-types, Braille and Masursky, have been imaged during flybys but at very low spatial resolution. In particular, only four objects have been orbited (Eros, Itokawa, Ceres, Vesta) for detailed investigation. It thus appears that we are only at the dawn of asteroid exploration.

We review below specific questions which justify a major *in situ* observational effort.

2.1. ASTEROIDS UNCONNECTED TO METEORITES

A large fraction of asteroid spectra are well matched by meteorite ones. Specifically, ground-based observations have revealed the following associations between asteroid and meteorite types:
i) Ch and Cgh types and CM meteorites;
ii) K types and CV, CO, CR, CK meteorites;
iii) X types and iron meteorites;
iv) V types and HED meteorites;
v) Xc types and ECs and aubrites;
vi) T types and Tagish Lake meteorite;
vii) Xk types ans mesosiderites;
viii) A types and pallasites and brachinites;
ix) S types and ordinary chondrites (∼80% of the falls).

There are however several asteroid types which are not represented in our meteorite collections (*e.g.*, B, C, Cb, Cg, D, L). Considering that these asteroids have nearly featureless spectra in the visible and near-infrared ranges, their surface composition has been and still is an open issue. In situ measurements (for instance, *via* Gamma spectroscopy) would help solving the question of their composition and thus of their origin.

2.2. METALLIC ASTEROIDS

General speaking, metallic asteroids (X-types) and their meteoritic counterparts (iron meteorites) are among the most perplexing and mysterious objects among solar system small bodies. It is still not understood how these asteroids with diameters up to 250 km (the asteroid Psyche) formed and what they actually represent. Are they remnant cores of primordial differentiated protoplanets or did they directly form as we see them today? In the first scenario, Psyche for instance would require that the mantle of a parent body of the size of Vesta (since Psyche's size is similar to Vesta's metallic core) has been totally blown off; if so, where has such a huge mantle gone? Whereas ground-based observations are unable to provide constraints, in situ observations will unambiguously help clarifying the question.

Another perplexing feature of metallic asteroids is their apparent low density ∼4-5 g/cm^3 to be compared with that of their associated metal-rich meteorites ∼7.8 g/cm^3. This implies significant porosity, comparable to that found in any other asteroid. How can this be the case? The remnant cores of differentiated bodies are not expected to have significant porosity but may still include a substantial fraction of silicates; however, this would be in contradiction with the existence of purely metallic meteorites. Clearly these questions can only be solved by in situ observations.

In situ observations of metallic asteroids will further allow studying for the first time their response to collisional impacts via the properties of the craters (size, depth, morphology). The cratering process has been investigated in the case of the silicate-rich asteroids of typical densities of 1.5 to 3.5 g/cm^3 visited by previous space missions already indicating significant differences in crater morphology between the low density (Mathilde) and higher densities (Lutetia, Vesta). We therefore expect to discover a new type of crater morphology and thus surface response to impacts on those metallic asteroids.

2.3. MULTIPLE ASTEROID SYSTEMS

Following the in situ discovery of the Dactyl satellite of asteroid Ida during the Galileo fly by, 83 multiple systems have been compiled in the main belt. The vast majority is binary (primary + one satellite) but four are triple (primary + two satellites). It is currently estimated that $\sim$5% of all main belt asteroids are multiple systems. Those systems present an outstanding potential for tackling new science questions. First, the orbit of the satellite(s) allows to directly determining the density of the primary. Second, their physical characterization sheds light on the overall process of satellite formation (probably post-collisional accretion as rubble piles) and their gravitational evolution (synchronous rotation? tidally controlled shape?).

No space mission has ever studied in detail a binary or even triple asteroid system. Visiting such a system therefore appears as a top priority for future missions.

3. THE FIRST INVESTIGATION OF THE INTERNAL STRUCTURE OF ASTEROIDS

3.1. INTERIOR OF PRIMORDIAL PLANETESIMALS: FINGERPRINT OF THE TIME OF FORMATION

Very little is known about the early thermal evolution and internal structure of asteroids. Meteorite measurements have provided some constraints (evidence of aqueous metamorphism, dehydration, thermal metamorphism, incipient melting and widespread melting with core formation) whereas density measurements performed either in situ or from the ground have provided the remaining elements of answer that are summarized below:

These measurements indicate that a significant fraction ($\geq$95%) of the smaller asteroids (D$\leq\sim$60 km) are under dense (Carry, 2012): their density is lower than that of their surface composition. These under-dense bodies have been interpreted as being pervaded by large cracks and voids in their interiors, resulting from cataclysmic impacts and subsequent uneven re-accumulation of material. The fraction of volume occupied by these voids is called macroporosity. Our current census of density and macroporosity for about 300 asteroids indicates that some asteroids may have macroporosities up to 50%.

Density measurements also indicate that large asteroids (D$\geq\sim$100 km) are far less porous (macroporosity $\leq$10%) than smaller ones; when coupled with the fact that large asteroids are prominently primordial protoplanets, this implies that their internal compositional structure holds invaluable clues on the earliest stages of their formation. By studying these objects, we can learn whether they are differentiated or not. Such information, in turn, holds invaluable constraints on their time of formation that are otherwise only accessible from meteorite measurements (*i.e.*, differentiated bodies formed earlier than undifferentiated ones). In case of differentiation, we can learn about their internal compositional structure such as the thickness and nature of the various layers. Of direct interest to the present topic, several researchers have recently shown that the distinction between primitive bodies and differentiated bodies might not be as simple as once thought. A paleofield in the primitive chondritic Allende meteorite has been detected, which is probably due to the presence of a dynamo, and therefore an iron core, in its parent-body (Carporzen *et al.*, 2011). This discovery not only blurs one of the fundamental frontiers in the solar system, that between chondrites and differentiated bodies, but also forces us to question whether our knowledge of asteroid surfaces is representative of their bulk.

Probing for the first time the internal structure of several asteroids will represent a giant step forward and specifically allow:

- deciphering the early thermal evolution of primordial asteroids,
- demonstrating whether all large asteroids are differentiated,
- understanding how the internal structure varies as a function of the surface composition,
- completing the chronology of the time of formation of the different asteroid classes that currently relies on meteorite measurements only,
- characterizing the internal effects of collisions (as of today, we have only studied the surface effects of collisions),
- explaining the origin of the mysterious grooves and crater chains.

Extensive groove systems have been observed on the Martian moon Phobos, and on asteroids Lutetia and Vesta whereas crater chains have been observed on asteroid Steins. It is currently proposed that the presence of voids beneath the surface could explain their origin.

4. THE ORIGIN OF WATER ON EARTH

4.1. ASTEROID AND COMETS AS PLAUSIBLE SOURCES

For decades, the source of Earth volatile has been a matter of intense debate. This topic is not only important in order to understand the origin of life on our planet, but also because it holds crucial clues on the early evolution of the solar system.

If the solar system was dynamically quiet early on, both planets and small bodies that formed inside the snow line were likely born *dry* (the Earth in particular) and volatiles would have been accreted at a later stage of Earth's evolution through impacts of volatile-rich asteroids and/or comets (Owen & Bar-Nun, 1995). On the contrary, if migration processes have been ubiquitous right after planetesimal formation (*e.g.*, Grand Tack, Walsh *et al.*, 2011), the Earth may have accreted *wet*. In the former case, the accretion of only a few C- type asteroids would have been sufficient to import the oceanic mass on Earth (Albarede, 2009; Alexander *et al.*, 2012). Whichever scenario is considered, the volatile composition of the Earth is governed by the volatile inventory of planetesimals, which were accreted by the planet.

When searching for the origin of Earth's water, and thus looking at the distribution of water across the solar system, it appears that water is present among all classes of planetesimals. Water has been detected on Kuiper Belt Objects (KBOs), on the moons of all giant planets, and on comets (Takir & Emery, 2012). Closer to the Sun, it has also been detected on main belt asteroids in various forms (Rivkin and Emery, 2010; Campins *et al.*, 2010; Licandro *et al.*, 2011). Specifically, hydrated minerals such as phyllosilicates have been identified both at the surface of asteroids, and in meteorites studied in the laboratory. These hydrated minerals can contain structurally bound OH or H_2O (some carbonaceous chondrites can contain up to 12% in water, see Takir & Emery (2012) for a review).

Water has also been detected on some asteroids as ice. Themis and Cybele for example, exhibit a spectral feature around 3 microns, which has been attributed to the presence of water ice at their surface (Rivkin & Emery, 2010; Campins *et al.*, 2010; Licandro *et al.*, 2011). Jewitt & Guilbert-Lepoutre (2012) suggested a scenario in which repeated impacts could steadily bring burried ice at their surface (provided water ice could have survived up to now).

Since water is ubiquitous among all classes of planetesimals, its detection per se on a given object does not specify which population(s) of small bodies contributed to Earth's water. An additional criterion is thus required to help discriminating among all plausible sources of water, namely the deuterium-to-hydrogen (D/H) ratio as discussed below.

4.2. FROM THE D/H RATIO TO MODELS OF THE SOLAR SYSTEM FORMATION

Because of its potential for constraining the origin of volatiles on Earth, the measurement of the deuterium-to-hydrogen (D/H) ratio in small bodies and meteorites has been the subject of intense efforts. Deuterium was synthesized during the Big Bang (Wagoner *et al.*, 1967) and is essentially believed to be primordial, since there is no known mechanism that produces significant amounts of D in galaxies or stars thereafter (Epstein *et al.*, 1976). The D/H ratio in water is very sensitive to the conditions prevailing in the environment in which it is formed. Isotopic exchange reactions occurred with an efficiency that depends upon the turbulent mixing in the solar nebula, correlated with gas density and temperature. This ratio is thus predicted to vary with heliocentric distance (see Robert (2006) for a review) and/or the time of formation. Therefore, objects that formed in the same source regions and at similar times should have accreted ice with similar hydrogen isotopic compositions. This implies that a comparison of water D/H values in comets and other solar system small bodies is potentially a direct test of the predictions of the dynamical models (*e.g.*, Nice model or Grand Tack model).

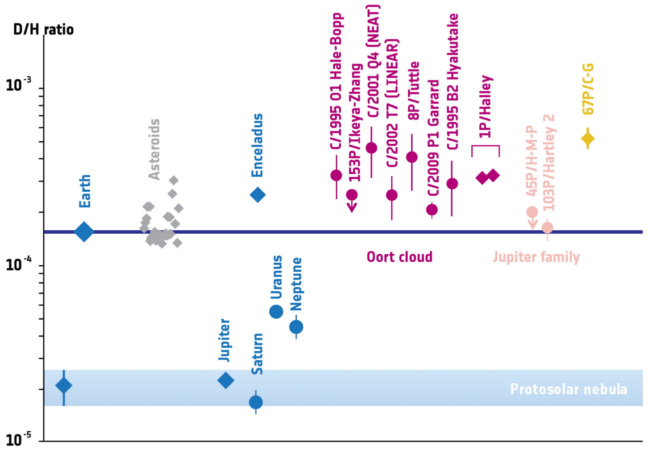

Fig. 3 – Comparison of the estimated D/H ratio of water in various chondrite groups (labeled here with Asteroids) with those measured in Oort cloud and Jupiter family comets (JFC), and Saturn's icy moon Enceladus (from Altwegg *et al.*, 2014).

Figure 3 summarizes the present state of knowledge of the D/H ratio among small bodies of the solar system. The marked difference between meteorites-asteroids and comets, that is between internal and external solar system objects, has long been assumed an essential property of the solar system, mainly based on the higher D/H ratio of comets (Robert, 2006). This dichotomy has been questioned by the measurement of the Jupiter family comet Hartley 2 whose D/H is identical to the terrestrial value and therefore closer to that of carbonaceous chondrites (Hartog *et al.*, 2011). This discovery strengthens the idea of a continuum between asteroids and comets (Gounelle *et al.*, 2011).

Overall, Figure 3 highlights that determining the origin of the water on Earth is a problem that is far more complex than solely constraining the D/H ratio for all classes of small bodies, although it is a necessary step. Indeed, the Earth cannot have formed solely by accretion of Jupiter family comets, as its bulk composition is not compatible with solely comets. It thus appears that constraining the origin of the water on Earth will also require constraining the isotopic composition for all classes of small bodies. Whereas this data partially exists via meteorites, it is obviously incomplete as certain asteroid classes are not present in our collections. It is thus mandatory to extend the reconnaissance of both the D/H ratios and the isotopic composition for all classes of small bodies that are not sampled in our collections. We should therefore avoid visiting the parent bodies of CI and CM meteorites (Ch and Cgh types) and primarily focus on water-rich B-, C-, Cb, Cg, T- or D-types.

Ultimately, knowing both the D/H ratio and the isotopic composition of all classes of small bodies will allow reproducing the composition of the Earth by identifying the correct linear mixture of end members. At the same time, they will allow identifying the source of its water.

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