What do small bodies tell us about the formation of the Solar System and the conditions in the early solar nebula?

A White Paper for the

Planetary Science and Astrobiology Decadal Survey 2023–2032

Commissioned by the Small Bodies Assessment Group

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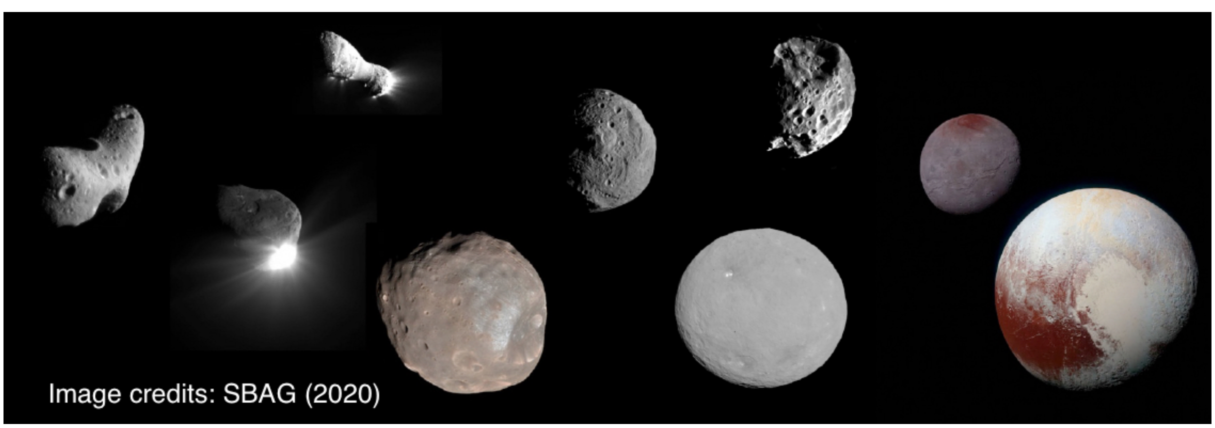

Executive summary

The desire to know how our Solar System came to be is a fundamental driving force for humanity's exploration of space. "*Building new worlds*–understanding Solar System beginnings" is a major cross–cutting theme in the 2010 Planetary Science Decadal Survey. Drastically improving our understanding of Solar System formation also has synergy effects. It provides unique information on one past protostellar system that helps astrophysicists understand stellar formation and protoplanetary disks. It provides context that increases the scientific return of missions exploring the current properties of the Solar System. **Exploration of small primitive bodies is the key to reveal the origin of the Solar System.** We conclude that substantial progress in understanding the formation of our Solar System during the 2023–2032 decade requires: 1) sample return missions to a Jupiter Family comet (ideally cryogenic) and/or Trojan asteroid to access primitive and previously unexplored types of material; 2) probing the interior of undisrupted primitive bodies with orbiters and placing decades of remote–sensing spectral information into a concrete mineralogical context with landers; 3) multi–body flyby missions to poorly explored target groups to better understand the diversity of body shapes and composition.

1 Introduction

The term "small bodies" refers to all Solar System objects that avoided accretion by the Sun, a planet, or their largest moons. This populous and diverse group includes meteoroids, near–Earth objects, main belt asteroids and comets, the Martian moons, Trojan asteroids, irregular satellites, comets, Centaurs, and trans–Neptunian objects in the Kuiper belt, Scattered Disk, Detached Scattered Disk, and Oort cloud. Sizes range from microscopic interplanetary dust grains to 1000 km–class dwarf planets. Recently, interstellar objects traversing the Solar System have been added to the list.

Small bodies enable unique research and exploration opportunities. Weakly processed objects preserve pre–solar material and substances formed in the solar nebula. Grains in such bodies reveal the physical conditions during which they formed, and the chemical processes active at that time. Grain aggregates in samples show the first steps in the accretion process that formed planets. Bodies experiencing thermal metamorphism, differentiation, magnetization, and aqueous alteration record ancient processes that no longer are active. Small bodies are our best windows into the earliest history of the Solar System, and there is strength in numbers. They sample material from a wide range of solar distances, they have been processed in different environments, and shuffled around by the planets. Collectively, their compositions and orbital statistics bear evidence of material mixing across wide spatial scales and of the planetary migration that changed the architecture of our Solar System.

Harvesting this treasure trove of information requires investments that lead to fundamental and not incremental advances. A top priority is to "Find and characterize new samples from small bodies through meteorites, micrometeorites, interplanetary dust, and returned samples from comets, asteroids, and other small bodies, particularly emphasizing material not available in the meteoritic record" (SBAG[1] 2020). Substantially increasing the number of well–observed small bodies requires that astrophysics assets are made available for Solar System observations. White Papers submitted in preparation of the Decadal Survey on Astronomy and Astrophysics 2020, or Astro2020[2], explicitly call for the usage of the LSST (Meech *et al.*), ELT (Trilling *et al.*), JWST (Hammel *et al.*), WFIRST (Holler *et al.*), ngVLA (Moullet *et al.*), the Arecibo Observatory, the Goldstone Solar System Radar, and the Green Bank Telescope (P. Taylor *et al.*; Virkki *et al.*[3]). Combined, this allows to "Study the elemental, isotopic, mineralogical, and molecular composition of small bodies (through ground–based spectroscopy, spacecraft analysis, returned samples, and samples of meteoritic material) to constrain [small bodies] origins" (SBAG[1] 2020).

Small body science provides unique and valuable input to astrophysics (see Astro2020[2] for references in this paragraph). Answers to questions about the composition of interstellar dust, sought through X–ray (Corrales *et al.*) and far–infrared polarimetry (Hensley) astrophysical observations, can partially be provided by pre–solar grains in meteorites and returned samples. Efforts in observational astrophysics to understand physical conditions and chemical processes in protostellar disks, e.g., dust coagulation (van der Marel *et al.*), the distribution of water ice and the role of magnetic fields and turbulence in stellar accretion (Jackson *et al.*; McGehee *et al.*), and the formation of pre–biotic molecules (McGuire *et al.*), benefit from knowledge of dust aggregation, magnetization, particle size sorting, and chemical composition of organics and ices in small Solar System bodies. Nucleosynthesis studies could benefit from small body samples, e.g., finding additional evidence from small bodies for a recent nearby supernova that deposited ^{60}Fe in lunar regolith (Fields *et al.*), better understanding the production of r–process elements (Binns *et al.*; Beers *et al.*), and of P, N, F, Cl, K elements that are difficult to observe in stars (Hinkel *et al.*).

2 Major Scientific Questions

In order to demonstrate current community interest in bridging the knowledge gap discussed here, the referenced papers in this Section are White Papers proposed for the Planetary Science and Astrobiology Decadal Survey[3]. We divide our topic matter into two categories: 1) the solar nebula, and 2) planetesimal formation, primary processing, and early migration.

Our current understanding of the solar nebula has primarily been reached through: i) in-

[1]SBAG (2020). Goals and Objectives for the Exploration and Investigation of the Solar System's Small Bodies. http://www.lpi.usra.edu/sbag/goals/

[2]The Astro2020 white papers mentioned in the text can be downloaded from the following link: http://www.nationalacademies.org/docs/DE0BDA7961FE2537EFCFE8220CE8395AC3B6BB41D8A3

[3]These papers are listed at https://www.lpi.usra.edu/decadal_whitepaper_proposals/

Major Scientific Questions I: Early Solar Nebula Conditions

The galactic birth environment of the Solar System
• What processes shaped the orbital distributions in the Detached Scattered Disk?
• What do oxygen and short–lived radionuclide isotopes say about the early stellar environment?
The properties and abundances of pre–solar material
• What was the contribution of surviving pre–solar solids from distinct pre–solar environments?
• Were organics synthesized in the interstellar medium, in the solar nebula, or inside small bodies?
• Have pre–solar ices survived in small icy bodies?
The physical conditions, processes, and chemical reactions in the solar nebula
• What were the redox state, temperature, and pressure gradients of the early Solar System?
• What was the level of magnetization in the solar nebula?
• What was the timescale of gas clearance from the Solar System?
• What flash–heating mechanisms melted, e.g., CAIs and chondrules?
• To what extent have protostellar phenomena (e.g., bipolar outflows, disk winds, FU Orionis outbreaks, X–ray flares) left an imprint on solar system materials?
• What is the distribution and origin of D/H ratios in different populations of icy bodies?
• What chemical reactions and isotopic fractionation processes did volatile materials experience?
The composition and transport mechanisms of the solar nebula
• What was the composition gradient in the formation locations of different small body populations?
• Does the carbonaceous / non–carbonaceous meteorite dichotomy reflect a heterogeneity in the physical and/or chemical conditions within the disk?
• What are the relative abundances of high/low temperature condensates in small bodies?
• What is the nature and structure of organics and ices in small bodies?
• What was the distribution of volatiles in the early Solar System?
• Was the spatial distribution of short–lived radionuclides homogeneous or heterogeneous?
• What was the extent of radial and vertical mixing in the solar nebula, including at its furthest reaches?
• How were high–temperature minerals like olivine transported to the regions of comet formation?
• What are the evidence for, and significance of, size–sorting of chondritic particles?
• What additional constraints do meteorites and asteroids provide about radial mixing in the early solar system?
The properties of the first grain assemblages
• What are the origins and genetic interrelations between CAI, agglomeratic olivines, amoeboid olivine aggregates, chondrules, and matrix material?
• Are chondritic grain types present in small bodies presently not sampled by meteorites? Are there other, currently unknown, grain types?
The timeline of solar nebula evolutionary processes
• What was the timing of the ^{26}Al injection with respect to the solar system formation?
• Relative to CAIs, when did chondrules form and did their formation overlap that of CAIs?
• How does the timeline of chondritic granular components compare with the evolutionary sequence established observationally for protostars?

Table 1: Major science questions regarding the solar nebula.

vestigations of meteorites and interplanetary dust regarding their mineralogical, chemical, and isotopic compositions, physical structures down to nano–scales, and age; ii) obtaining context from astrophysical observations of protostars and gas/dust disks; iii) reaching a theoretical understanding of protostellar collapse and accretion through magneto–hydrodynamic simulations and models of chemical reaction networks; iv) experiments on grain agglomeration in drop towers, parabolic flights, and in space. The first steps have been taken to collect samples from comets (Stardust) and S–type asteroids (Hayabusa), with samples from C–type asteroids expected soon (OSIRIS–REx, Hayabusa 2). JAXA and NASA plan a sample return mission to the Martian moons (MMX).

Table 1 summarizes major questions about the solar nebula. The majority of these questions are **best addressed through samples of small bodies**, in the form of meteorites (Ishii and Corrigan) or material brought to Earth through sample returns (including interplanetary dust particles; Horanyi *et al.*), preferably cryogenic ones that include volatiles (Milam *et al.*; Westphal). Cryogenic sample–return is the most powerful technique (Jacobson and Bose), by preserving the contextual information of samples and parent bodies, by enabling sampling of bodies not represented in the meteorite collections (unaffected by atmospheric entry and weathering), and by fully utilizing the capacity of Earth laboratories (Iacovino *et al.*), including habitability investigations (Castillo–Rogez *et al.*).

Table 2 summarizes major questions about planetesimal formation and evolution. Progress in understanding planetesimal formation requires **exploring small body interiors** (Eubanks and Bills; Haynes *et al.*; Landis *et al.*), with the first steps taken by the Rosetta/Philae rendezvous mission to comet 67P/Churyumov–Gerasimenko. Part of the problem of interpreting body shapes in terms of formation stems from limited capabilities of current formation and collision models to make quantitative predictions of observable properties that can be cross–checked against spacecraft observations. Testable hypotheses that distinguish, e.g., a gravitationally collapsed pebble swarm from a collisional rubble–pile, are needed. This requires improved laboratory measurements of how highly porous and icy materials behave mechanically, and availability of top–end computing facilities to perform numerical simulations of planetesimal formation, collisional, and tidal evolution.

Ground–based surveys have discovered thousands of TNOs with a complex dynamical structure as a population and poorly understood distributions of albedos, colors, and spectral signatures. Similarities and differences between these distant objects and Centaurs, comets, Trojans, main belt comets, and carbonaceous asteroids in the main belt and near–Earth population have gradually been established. In parallel, advances in our understanding of planet migration and the resulting reshuffling of small bodies within the Solar System has reveal an unexpected complexity as well as novel research opportunities. How do we simultaneously reconstruct the original compositional gradient of the Solar System, and use the currently observed distributions of orbits and spectral properties to glean insight into when and how planetary migration happened? **What do the observed albedos, colors, and spectral features mean in terms of mineralogical and chemical composition?**

Major Scientific Questions II: Planetesimal formation

The planetesimal–forming mechanisms that were active in the early Solar System
• How did accretion proceed through various size regimes? • What were the effects of the "snow lines" of water and other volatiles, and electrical charging? • How do binary and multiple systems form? • Are bilobate shapes and high porosities typical outcomes of early formation? • What do the physical and chemical properties of the deep interior of small bodies tell us of their formation, and how can that information be accessed? • Is the layering seen on comets a result of formation, evolution, or some combination? • Did planetesimal formation in the solar nebula and in giant planet accretion disks proceed differently?
The mechanisms responsible for thermal processing and their effect on planetesimals
• Was ^{26}Al present in the outer Solar System at the time of planetesimal formation? • Have small currently icy bodies experienced aqueous alteration?
The timeline of formation and primary processing of small bodies
• When did chondrites accrete, compared to the differentiation of the parent bodies of iron meteorites and achondrites? • When did aqueous alteration of chondrites start, and how long did it progress? • When did the planetesimals in the outer Solar System form, relative to bodies sampled by meteorites?
Catastrophic disruption of small bodies
• Are comets original planetesimals or fragments of larger bodies? • To what extent have dynamically cold Kuiper belt objects survived intact?
The mechanisms, extent, and duration of planetesimal migration
• What is the distribution of asteroids and how has material migrated from where it initially formed? • Did Main Belt comets form in place or did they migrate to their current locations? • Did the Jupiter Trojan asteroids originate near Jupiter's orbit or farther our in the Solar System? • Where and how did the irregular satellites of the giant planets form? • How was the Kuiper Belt dynamical structure modified by giant planet migration? • When were comets moved from their place of formation to their current major reservoirs in the Scattered Disk and Oort cloud? • What was the source region of TNOs and what do small bodies reveal about planet migration?
Interstellar dust, asteroids, and comets
• What is the nature of interstellar objects? Are they more likely to be icy or rocky? • What do interstellar objects tell us about their original accretionary environment? • What does a mix of active and inactive objects tell us about the processes that bring them to us? • What do the observed properties of interstellar objects tell us about conditions during the period of planetary migration in our Solar System?

Table 2: Major science questions regarding planetesimal formation, processing, mixing.

Flybys of several comets by Deep Space 1, Stardust, and Deep Impact, and of one dynamically cold TNO (Arrokoth) by New Horizons, combined with radar observations of comets passing near Earth, revealed that bilobed shapes and low porosities seem common in the outer Solar System. Observations of Centaurs and dynamically cold TNOs have revealed ultra–wide binaries and triple systems. Progress in understanding planetesimal formation, and the role of collisional cascades in the outer Solar System, requires a **larger sample of well–resolved small bodies to understand the diversity of shapes and system properties** (Brisset *et al.*), including irregular giant planet satellites (Holt *et al.*).

For decades, thermal metamorphism, differentiation, and aqueous alteration has been studied in meteorites. More recently, the exploration of Vesta by Dawn, and the upcoming Psyche mission to a stripped metal core, have initiated a much needed in situ investigation of small bodies that were processed early and heavily. Similarly, Dawn's exploration of Ceres (Castillo–Rogez *et al.*), and the OSIRIS–REx and Hayabusa 2 sample returns to C–type asteroids, enhance our understanding of aqueous alteration in a parent–body context. However, we do not know if such processes were active in the outer Solar System or when they took place. Answering this will require combined investigations of samples (detailed mineralogy and radiogenic dating), in situ exploration (photometric/spectroscopic surface units with associated crater counts, magnetic fields; Villarreal *et al.*), and telescopic population studies. The discovery of new targets and their characterization must be ramped up, and dynamical studies need to continue with increased intensity. Such efforts are also needed to place interstellar objects – that must be discovered in greater numbers to form a statistical sample – into a Solar System context, and to provide targets for reactive missions (Meech *et al.*).

3 Recommendations

We here outline top priorities in the exploration of small bodies in the next decade. We remind that this priority list exclusively concerns activities that will significantly advance our understanding of the solar nebula, and the formation and the early physical and dynamical evolution of planetesimals. The numbered list is in order of importance.

1. Sample return. Missions should target the least altered objects within reach. Non–cryogenic sampling of refractories at a Jupiter Family comet, or a D/P Trojan asteroid, is possible within the New Frontiers cost cap. A cryogenic sample from a Jupiter Family comet, using technology capable of retrieving (through deep drilling) and preserving amorphous water ice and/or CO_2 ice with super/hyper–volatiles trapped within would require a Flagship mission. Return missions should have collectors for interplanetary dust particles.

2. Internal structure and surface composition. Medium–sized ($\sim 100\,\mathrm{km}$) MBAs, Trojans, or Centaurs have the highest probability of being undisrupted and simultaneously not being heavily thermally processed. Radar tomography, gravity field radio science, and magnetometry with one or several orbiters would reveal the preserved signatures of the mechanisms forming such bodies. A lander with an advanced on–board laboratory to determine mineralogy and chemistry of organics would establish the relation between composition and remote–sensing spectral properties that helps interpreting telescopic population studies. Priority should be given to targets not represented in the meteoritical record, or with properties that differ significantly from bodies studied by prior missions. Orbiter and lander missions could be done separately within the Discovery program, or more efficiently, combined into a single larger mission.

3. Body shapes and surface composition. Advancing our knowledge on the diversity of body shapes and surface compositions from remote sensing requires multi–target flyby tours. The usage of SmallSats and CubeSats (including fleets) in this context should be promoted. Higher priority should be given to target types that differ markedly from those already studied, including dynamically new comets and interstellar objects. NEOs, MBAs, and JFCs remain important flyby targets. Giant planet missions should include en route Centaur flybys and irregular satellite studies when possible.

Telescopic observations. Continue the search for new objects and populations with Pan–STARRS, the Catalina Sky Survey, and eventually NEOSM. Characterize their properties with Keck, IRTF, HST, NEOWISE, SOFIA, the Arecibo Observatory, the Goldstone Solar System Radar, and the Green Bank Telescope. Secure access to astrophysics assets like LSST, ELTs, JWST, WFIRST, ALMA, and ngVLA. Establish links between dynamics, composition, body shapes and presence of rings (e.g., from stellar occultations), and spin properties.

Laboratory work. Improve and develop radiogenic dating techniques for returned/delivered samples. Develop techniques to analyze and store cryogenic samples. Measure properties of porous and icy materials and response to shock. Develop spectral libraries further. Study dust coagulation in cryogenic conditions, including amorphous water ice and electrically charged particles.

Theory and modeling. Invest in planetesimal formation and disruption numerical simulations. Continue studies of dynamical migration and internal planetesimal evolution.

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