Asteroids

Community White Paper to the Planetary Science Decadal Survey, 2011-2020

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Abstract

The term "Asteroids" within this white paper includes the main belt asteroids (MBAs) and Jupiter Trojans, exclusive of Near-Earth Objects (NEOs), Centaurs or Trans-Neptunian Objects (TNOs), and Ceres, each of which are covered under other separate white papers. The sheer diversity of asteroids is their most compelling feature. They are a reservoir of information on a huge range of solar system history, chemistry, physical processes, and evolution. Because they often are collisional fragments, asteroids are windows into processes that are hidden on the terrestrial planets by time, geochemical evolution, or simply deep burial. Finally, asteroids are accessible to our exploration. Their low gravity and abundant numbers provide multiple opportunities for science missions to provide exceptional insights into how our solar system formed and has evolved.

I. Subdiscipline Overview

Asteroids have been shown to be complex worlds with a range of morphologies, dynamical histories, and structural evolution that responds to a staggering range of solar system processes. Each has a history to unravel beginning in primordial times, when the entire solar system, including our own planet, was forming. The physical nature, distribution, formation, and evolution of asteroids are fundamental to our understanding of how planet formation occurred and, ultimately, why life exists on Earth. In our current solar system, primitive or undifferentiated asteroids (and comets) are the most direct remnants of the original building blocks that formed the planets. As such, some of them may contain a relatively pristine record of the initial conditions that existed in the solar nebula some 4.6 Gyr ago.

The asteroids that have survived since that epoch have, however, experienced numerous collisional, dynamical, and thermal events that have shaped their present-day physical and orbital properties. Through interpretation of this record via observations, laboratory studies of extraterrestrial materials (both meteorites and returned samples), and theoretical/numerical modeling, we can learn much about the time-evolution of the bodies in our solar system, enabling a better reconstruction of the initial conditions. Asteroids provide the missing context for both primitive and evolved meteoritic data and thus play a central role in understanding terrestrial-planet formation and the evolution of the solid material in the solar system.

Even though asteroids represent only a tiny fraction of the total mass of the terrestrial planets, their large numbers, diverse compositions, and orbital distributions provide powerful constraints for planet formation models. For example, in the inner solar system, the orbital and physical characteristics of the asteroid belt and the surfaces of the terrestrial planets scarred by asteroid impacts can be used to narrow the range of possible starting conditions that can conceivably create a planetary system similar to our own. While the dynamical properties of the terrestrial planets (e.g. masses, heliocentric distances, spin rates, obliquities) also provide valuable constraints, many of these characteristics may have been significantly influenced by large collisions and other stochastic events, potentially making it problematic to reproduce these traits in any modeling effort. Moreover, other useful constraints, such as a planet's geochemical and isotopic characteristics, are often difficult to interpret because each of the terrestrial planets has experienced extensive differentiation and thermal evolution with unknown starting conditions. Thus, asteroids and other small body populations may provide key pieces of the puzzle that allow us to decipher why at least one of the planets in our solar system harbors life.

II. Top-Level Scientific Questions

What was the compositional gradient of the asteroid belt at the time of initial protoplanetary accretion?

- What are the physical properties of asteroids?
- How do surface modification processes affect our ability to determine this structure?
- What is the population and compositional structure of the main asteroid belt today?
- What does the composition (mineralogy/chemistry) of asteroids tell us about the redox and thermal state/gradient of the early solar system?
- How do dynamics and collisions modify this structure over time?
- The degree of mixing/transport in the asteroid belt offers a glimpse into solar-system wide transport. Were TNOs implanted in the outer asteroid belt and did differentiated asteroids evolve from the inner solar system?

What fragments originated from the same primordial parent bodies, and what was the original distribution of those parent bodies?

- What asteroid fragments are associated dynamically, suggesting a common origin?
- What asteroidal families are favorably placed in the main asteroid belt (MB) to be represented in meteorite collections? Which are in dynamical proximity for Yarkovsky transfer and MB resonances that serve as likely sources of NEOs?
- What asteroidal bodies are geochemically linked?

What do asteroids tell us about the early steps in planet formation and evolution?

- What are the compositions and structures of surviving protoplanets?
- What does their cratering record combined with the cratering record of younger surfaces (planetary surfaces and fragments of protoplanets) reveal about the earlier size distribution of objects in the MB?
- What do meteorites tell us about formation and evolution processes of these bodies? How well do they sample the population of primitive bodies in the solar system?
- What can primitive meteorites tell us about the first stages of planetesimal accretion?
- What are the benchmarks for early solar system conditions and processes shaping its evolution?

What are the characteristics of asteroids as individual worlds?

- How do thermal-related processes such as differentiation, magnetism (remnant from an ancient core dynamo), volcanism, and hydrothermal alteration proceed?
- What are the characteristics of water-rich and/or hydrated asteroids? How do hydrothermal processes drive internal evolution, the development of brines, and formation of organic material?
- Do the variations water-rich spectral classes reflect compositional stratification?
- What are the similarities and differences between small (and difficult to observe) main-belt asteroids and comparably sized NEOs? Can NEOs serve as surrogates for the properties of small MBAs?
- What are the densities of the large asteroids and family members?
- What are the key surface processes (e.g., impact cratering, tectonics, regolith development / movement into "ponds", and space weathering) that act on small bodies?
- How do these processes vary with composition, gravity, and solar distance?

- What is the relationship between composition and surface roughness of asteroids as seen in radar polarization data? What are the implications of this for porosity, mineral cleaving and strength of these objects?

III. Required Research and Research Facilities

Ground-Based and Space-Based Surveys: Asteroids are fundamentally diverse, with an enormous range of sizes, shapes, spins, compositions, densities, orbits, single/binary/multiple configurations, and evolutionary histories. To prepare for and support future missions to asteroids, it is essential to have strong R&A programs to characterize their spectral and physical properties, to understand the meaning of the multiple spectral classes, and to assess their collisional and dynamical histories. To address the top-level science questions most cost-effectively requires not only state-of-the-art instrumentation and telescopes, but better access for planetary research to those facilities through enhanced support/partnership in those facilities (e.g., NASA/Keck access). Past work has demonstrated the value of such work to NASA missions, with contributions by small-to-large facilities including radar, ground-based telescopes, adaptive optics, and space-based telescopes with projects ranging from the study of a single object to surveys of hundreds of thousands of asteroids. Many MBAs are accessible from small-to-moderate aperture facilities for studies of photometry and stellar occulations, offering opportunities for undergraduate research experience. Currently, radar can image closer MBAs, providing critical information on shapes, sizes, and possible satellites; this effort needs continued support. Using adaptive optics on 8-10m class telescopes, a few hundred asteroids can be sufficiently resolved to determine their size, shape and pole orientation, and many hundreds more can be studied for the presence of satellites. Study of binary and multiple asteroids in the MB yields vital insights: i) asteroid density, a fundamental property, ii) collisional history, , and iii) the origin and delivery of single and multiple objects to NEO space. Observations of large numbers of asteroids will also be acquired from space-based astrophysics surveys such as LSST and the ESA Gaia mission and will need to be analyzed.

It is vital and extremely cost-effective to maintain state-of-the-art instrumentation on ground-based telescopes. The SpeX instrument on NASA's IRTF remains the only dedicated spectrograph for small body research for US institutions. While SpeX has dramatically improved the quality and quantity of asteroid compositional studies, the telescope's relatively small size (3.0 m) limits mineralogical characterization. Much cutting-edge science will depend on better access to larger telescopes. The increased light-gathering power of an 8-10m-class telescope is vital to push spectral studies to the range of the small objects (e.g., young asteroids) that is are of great importance. Important science and mission-support objectives in the MB and Trojans can only be addressed by developing a dedicated 8-10m-class telescope equipped i) with a low-resolution spectrograph working simultaneously in visible and near-infrared (eq. to X-Shooter) and ii) an efficient adaptive optics system (e.g., Keck AO). In addition, larger apertures, such as the TMT will provide an enormous advantage to imaging programs, increasing the angular (spatial) resolutions by a factor of 3, and boosting the number of objects accessible substantially. Airborne observatories (e.g., SOFIA) and balloon-borne missions (Hibbitts et al.) are essential to characterize the size, albedo and surface properties of SSSBs. Access to these new facilities will be essential.

Study of Asteroid Families: Dynamicists have been able to use asteroid families to date collisional events and explain the IRAS dust bands. Evidently most of the (especially smaller) MBAs are members of comparatively few large families that were formed subsequent to the Late Heavy Bombardment (LHB) and may retain evidence of the nature of the main-belt asteroid population during and prior to the LHB. Small asteroid "clusters", which can be dynamically dated with high precision, lose coherence and delectability after several tens of millions of years. Studies of the youngest families and clusters can help us understand time-dependent processes that affect asteroids on short timescales, such as spin evolution (e.g. due to YORP), space weathering, sublimation of surface volatiles, etc. In addition, younger fragments may preserve primordial stratigraphy from their parent asteroid, providing unique windows into planetary differentiation and evolution processes. Studies of the properties of older families can tell us how collisionally produced size distributions and orbital distributions evolve over timescales up to billions of years. While impact experiments in laboratories are crucial to validate numerical models of fragmentation at centimeter-scale, asteroid families are a natural laboratory for understanding the outcomes of large-scale catastrophic disruption.

Meteorite Studies: Most meter-sized meteoroids delivering meteorites to Earth come from the main asteroid belt (e.g. Trigo-Rodríguez et al., 2006). It is important to obtain dynamical information on bolides from fireball monitoring programs to better understand the primary delivery mechanisms, and determine which MB regions are best sampled by the meteorite collections. As demonstrated by the recent fall in the Sudan of 2008TC3 (Jenniskens et al., 2009), this is an international effort that depends on rapid and open communication. Asteroid studies would be greatly aided by the collection of spectral data as a regular part of the meteorite classification and curation process. Spectral absorption features are temperature-dependent, so laboratory studies of meteorites and minerals at low temperature can improve interpretation of telescopic and spacecraft-based asteroid spectra

Theoretical Studies: Theoretical/computational studies of planetesimal formation mechanisms, and comparisons with the meteorite/asteroid data, will constrain their origin. The goal is to find out what formation mechanisms are most consistent with (i) the likely primordial asteroid size distribution and (ii) meteoritical evidence that planetesimal accretion lasted several millions of years (cf. the range of chondrule ages in different meteorites and the time gap between CAIs and chondrules). Dynamical models of solar system evolution will help further constrain the origins of different asteroid types, and are already suggesting that the irons, outer-belt asteroids, and Trojans, may have originated from regions far from their current locations. Given that, which asteroids did form in their current locations? Dynamical models of meteorite/NEA delivery, especially in relation to stochastic events like family formation (e.g. Bottke 2007) can constrain meteorite source regions and help provide "ground-truth" for the mineralogy of families.

Impact Studies: Laboratory collisional studies can be used to calibrate hydrocode models of catastrophic disruption, leading to improved estimates of disruption scaling laws for a range of material types (e.g. porous, solid, ice-rich) at scales for which self-gravity can be neglected. Once validated by small-scale experiments, numerical simulations of fragmentation can then provide scaling laws over a range of sizes and energies adapted to asteroids larger than a few hundreds of meters. Comparing disruption scaling laws to those obtained by fitting asteroid collisional evolution models to the observed asteroid population can be used to infer population-averaged material properties (e.g. porosity, strength, and bulk density).

PDS: All asteroid mission data are archived in the NASA Planetary Data System. However, only a fraction of ground-based asteroid observations from NASA-funded programs are archived. Archiving of ground-based data should be funded to maximize the science return from observing programs. At the same time, these data are heterogeneous in format and content and PDS needs to provide adequate tools to researchers for the identification of data in the archive.

IV. Recommended Technology Development

Developments of a range of technologies are needed to enable small-body missions are discussed below. These capabilities are applicable to missions to every other class of small bodies covered in other white papers.

Propulsion: Low-thrust propulsion will be necessary for rendezvous missions or multiple asteroid flyby tours. Operational experience has shown that additional investment in electric propulsion technology is needed to ease operational difficulties. For missions beyond Mars orbit, the use of nuclear power systems instead of solar arrays has major advantages including eliminating structural problems with large solar arrays during contact with a small body for sampling, power degradation from dust deposition, and the inverse square degradation with heliocentric distance. Development of nuclear power systems and maintaining adequate supply of radioisotopes is recommended.

Telecommunications: Science data return is often limited by communication bandwidth, so development of infrastructure to raise bandwidth limits is advised. Upgrading to four or more 34m antennae at each DSN location is recommended as a cost-effective alternative to the maintenance of 70m antennas or the development of large arrays of micro-antennas. Optical communication holds promise for tremendous downlink and navigation capability, but is in need of significant development.

Sensing: To better enable surface-relative navigation and proximity operations, and for asteroid gravitational/dynamical model determination, development of fast imagers with wide field-of-view for use in low-light conditions and lightweight medium-range LIDARs and/or altimeters is recommended. Structured light systems can enable use of visual imagers for direct ranging. Gimbaling of sensors can greatly enhance science return by decoupling the image planning process from spacecraft body pointing. Lighter and lower-cost gimbal systems should be developed. For missions intended to contact asteroid surfaces, reliable technologies to prevent or eliminate dust accumulation on sensor optics should be developed.

Proximity Operations: Missions including close proximity operations or "landing" at asteroids require autonomous onboard GN&C that represents a substantial extension from existing systems. Difficult-to-predict forces and torques upon surface contact will challenge any landing spacecraft's GN&C, necessitating development of ascent control strategies to insure safe departure. If a surface-sample-ejector is used, challenges in tracking and capturing the sample canister will replace those of surface contact. Autonomous onboard planning, sequencing, and commanding systems capable of dynamically reacting to conditions can provide greater mission reliability, reduced costs, and enhanced science return. From Hayabusa, it was learned that autonomous fault detection and correction are needed. Increased support for basic research into autonomous onboard GN&C and planning, within the context of the unique astrodynamical environment close to asteroids, navigation, and orbit-determination research and methodology development appropriate to visiting asteroid systems is recommended.

Sampling Mechanisms and Surface In-Situ Science: A wide spectrum of ideas for asteroid surface-sampling mechanisms exist, each requiring technology development. These include sticky-pads, brush-wheel samplers, corers, and surface sample ejectors. Mechanical and actuation support must accompany these sampling mechanisms, in addition to transfer mechanisms to move sampled material to in-situ analysis instruments or an Earth return capsule. For all sampling methods, techniques should be developed to reliably measure the mass of material collected. For in-situ science, probes and small landers need to be developed that can accommodate a range of instrumentation from seismographs to mass spectrometers.

Flight Qualification: Small development and flight qualification missions to raise the TRL of the recommended technologies may be advisable, particularly if done through university partnership programs to lower costs and realize other engineering / science education goals.

V. New Frontiers Class Mission Priorities (listed in order)

Trojan Rendezvous: The Trojan asteroids are important targets because they i) represent primitive mineralogies that are not in the meteorite collection; ii) have potential to provide constraints on dynamical models of the early solar system; and iii) preserve evidence of early solar system volatile-rich processes. We point readers to the NOSSE report and a white paper centering on the Trojan asteroids submitted by Rivkin et al. A Trojan rendezvous with spacecraft equipped for geochemical remote sensing and in-situ surface probes/landers can significantly advance our knowledge of this link between the terrestrial planets and the outer solar system.

Multiple Flybys of MB: Some of the science goals of a rendezvous mission such as shape, surface processes, and mineralogy, and evolution of these objects may be at least partially achieved via a fly-by mission that targets multiple objects representing a range of poorly understood spectral types. While the spacecraft may be relatively simple, scope, length and complexity of the operations would put it into the NF class.

Multiple MB Rendezvous: The diversity of the MB population includes a number of types unrepresented or poorly represented, among NEOs and the meteorite collections. As with the Trojans, these asteroids sample mineralogies, initial conditions, surface processes, and dynamical evolution that can provide insight into the formation of the solar system but that are currently unknown. A multiple MB rendezvous targeting poorly understood spectral types (e.g. D, P, M, K) with a spacecraft equipped for geochemical remote sensing and in-situ surface probes/landers can significantly advance our knowledge of these unknown types and their unknown processes. This type of mission allow us to "type section" the geology, mineralogy, and dynamical evolution of thousands of objects in poorly characterized spectral classes better understand the role of the diversity in the asteroid belt in the formation of the solar system.

MB Sample Return: For asteroid spectral types that are probably not represented in the meteorite collection, sample return provides geochemical precision and characterization that is unmatchable with in-situ instruments. A MB sample return mission targeting poorly understood spectral types (e.g. D, P, M, K) with a spacecraft equipped for geochemical remote sensing and sample return can significantly advance our knowledge of these unknown types and their unknown processes.

VI. Discovery Science Goals

Because of the rich variety of targets in the main belt, regular Discovery missions to asteroids can address all top-level science questions. Many MBAs would make intriguing targets for both modest and highly ambitious spacecraft missions. Priority targets are listed below:

D/P-type Asteroid Rendezvous: Spectroscopically, these unusual asteroids are very similar to many outer solar system objects (e.g., comets, Trojans, irregular satellites, Kuiper belt objects). According to recent dynamical models, perhaps all of these objects came from a disk of comet-like objects originally located beyond the Jovian planets. D/P-types may be transplanted Kuiper belt objects now located within relatively easy reach of our spacecraft to understand in detail the mineralogy and processes of these primitive objects.

Themis Family and the MB Comets Rendezvous: The Themis family, produced by one of the largest disruption events in MB history, is filled with primitive objects. Family members display C-, D-, and B- type surfaces that could provide a window into the compositional stratification in the parent body and the aqueous alteration processes that may have been common in the early evolution of primitive bodies. One of the most interesting objects is MB comet 133P/Elst Pizzaro, which apparently formed via the breakup of a 20 km asteroid within the Themis family less than 10 My ago (Nesvorny et al. 2008). 133P/Elst Pizzaro may be a fragment from the icy mantle of the Themis parent body and preserve a history of parent body alteration.

M-type Asteroid Rendezvous: These worlds may have been the cores of differentiated objects potentially as large as (4) Vesta. As such they are windows into stratigraphical regions that cannot be reached on terrestrial planets and hold a range of important information on planetesimal formation in the inner solar system. Potential targets include (16) Psyche, (22) Kalliope, and (216) Kleopatra.

K-type Asteroid Rendezvous: Spectroscopically, these objects look like a cross between S- and C-type asteroids. Some claim they are the source bodies for the CV carbonaceous chondrites that are rich in calcium-aluminum inclusions, the earliest solids to form in the solar nebula. This makes their origin of prime importance to planet formation modelers: how, where, and when did these objects form?

Trojan and MB Asteroid Flybys: Trojan asteroids have been identified as a high priority target for New Frontiers missions. We note that some of the NF science goals for such as shape, surface processes, and mineralogy, and evolution of these objects may be achieved via a Discovery-level fly-by mission. Opportunistic flybys during other missions such as the up-coming Europa-Jupiter flagship are another low-cost way of doing significant science. Too often in the past these flyby opportunities were viewed as expensive diversions of scarce resources by mission management. Funding should be provided to support the operational costs involved so that the parent missions are encouraged to undertake these asteroid science goals.

Multiple Asteroid System Rendezvous: Approximately 80 multiple asteroid systems are known in the MB. Binaries among the larger MB asteroids are almost certainly due to collisions, although at least three distinct collisional processes are responsible. Each is expected to show distinct characteristics and we believe we have examples of each. At least two of those are well modeled numerically. YORP spinup and splitting is currently invoked as the mechanism for the smaller MB binaries. Detailed exploration of several multiple-asteroid systems by a spacecraft would address a range of critical science issues, including the collisional evolution of asteroids.

VII. Balancing Priorities

A systematic effort to characterize compositional, dynamical, and physical properties of asteroids, and providing a theoretical framework to explain these properties, requires stable support of new and current facilities (Keck, IRTF, and an 8m class telescope), as well as research and analysis programs. These programs allow foundational work that defines future asteroid missions and the interpretation of data from those missions. They also provide and train the science personnel required for such missions. The stability of these programs should be given high priority. In the event of mission cost overruns without cancellation, offsets must be sought from other mission programs to maintain the critical research and analysis support. Because of the ability of Discovery class missions to cumulatively address all of the top-level science questions identified here, asteroids should be a major priority of the Discovery Program. New discoveries may mandate short-term focused research programs and may reorder mission priorities, however they should not undermine the stability of the supporting research programs.

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