Goals and Objectives for the Exploration and Investigation of the Solar System's Small Bodies

Small Bodies Assessment Group (SBAG)

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2016 SBAG Chair and Goals Document Lead:
Nancy L. Chabot, Johns Hopkins University Applied Physics Laboratory

Goal 1 – Small Bodies, Big Science:
2016 Lead: Tim Swindle, University of Arizona
2016 Committee: Kieran Carroll (Gedex); Julie Castillo-Rogez (JPL); Will Grundy (Lowell Observatory); Emily Kramer (JPL); Joe Nuth (NASA Goddard); Carol Raymond (JPL); Andy Rivkin (APL); Heather Smith (NASA Ames)

Goal 2 – Defend Planet Earth:
2016 Lead: Tommy Grav, Planetary Science Institute
2016 Committee: James Arnold (NASA Ames); Brent Barbee (NASA Goddard); Steve Chesley (JPL); Paul Chodas (JPL); Leviticus A. Lewis (FEMA); Paul Miller (LLNL); Angela Stickle (APL); Timothy Titus (USGS)

Goal 3 – Enable Human Exploration:
2016 Lead: Paul Abell, NASA Johnson Space Center
2016 Committee: Brent Barbee (NASA Goddard); Josh Hopkins (Lockheed Martin); Sam Lawrence (Arizona State University); Stan Love (NASA Johnson Space Center); Carrie Nugent (IPAC); Andy Rivkin (APL); Mark Sykes (PSI)

Given the regularly occurring advancements that relate to our knowledge of the Solar System's small bodies, updates and reviews to this document are planned on a yearly basis, with input solicited from the entire SBAG community. The revision schedule is likely to utilize the twice-yearly SBAG meetings, which occur in January and June, with revision leads identified in January, a revised document made available for comments to the entire SBAG community in June, and the updated document finalized shortly afterwards.

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Executive Summary

The Small Bodies Assessment Group (SBAG) was established by NASA in 2008 and is composed of members with knowledge and expertise of small bodies throughout the Solar System. Membership in SBAG is open to all interested individuals of the interdisciplinary small bodies community. The term of "small bodies" refers to a wide-ranging, highly diverse, and numerous set of Solar System objects, including near-Earth objects, main belt asteroids, the Martian moons, comets, Trojan asteroids, irregular moons of the outer planets, centaurs, Kuiper belt objects, other trans-Neptunian objects, dwarf planets, dust throughout the Solar System, and meteorites and other samples of such bodies. This SBAG Goals Document captures the high priority objectives and unique exploration opportunities related to the Solar System's small bodies.

The SBAG Goals Document identifies three overarching, high-level goals pertaining to the Solar System's small bodies:

- ***Goal 1: Small Bodies, Big Science.*** Investigate the Solar System's formation and evolution and advance our knowledge about the early Solar System conditions necessary for the origin of life through research and exploration uniquely enabled by small bodies.

- ***Goal 2: Defend Planet Earth.*** Understand the population of small bodies that may impact our planet and develop ways to defend the Earth against any potential hazards.

- ***Goal 3: Enable Human Exploration.*** Advance our knowledge of potential destinations for human exploration within the small body population and develop an understanding of the physical properties of these objects that would enable a sustainable human presence beyond the Earth-Moon system.

These three goals are each of high intrinsic importance independent of the others, and each is treated as equal in priority. Similarly, numbering within each section does not reflect prioritization but rather serves to organize the main objectives of each goal. Overall, investigations that provide fundamental, rather than incremental, advances in any of the objectives are of the highest priority. The SBAG Goals Document also strives to present the overarching goals and objectives that motivate and drive small bodies missions, investigations, and exploration while not defining or limiting the implementation approaches that can be used to achieve these objectives. Given the regularly occurring advancements that relate to our knowledge of the Solar System's small bodies, updates and reviews of the SBAG Goals Document are planned on a yearly basis. It is expected that the goals and objectives detailed in this document will evolve over time, making it crucial to regularly re-evaluate if the three overarching goals and their associated objectives are capturing the current state of the diverse and varied fields that contribute to investigations of the Solar System's small bodies.

For Goal 1, small bodies provide unique scientific opportunities to investigate the formation of the Solar System. They represent remnants of the building blocks of the planets and provide insight into the conditions of the earliest history of the Solar System and the factors that gave rise to the origin of life. Small bodies also experience a myriad of processes, providing numerous natural science laboratories to gain knowledge into the evolution of the Solar System. Five high priority objectives are identified to support Goal 1. Additionally, this section of the SBAG Goals Document contains brief supplements that highlight how these high-priority objectives apply to different small bodies populations in the Solar System.

1.1. Understand the census and architecture of small bodies in the Solar System;
1.2. Study small bodies to understand the origin of the Solar System;
1.3. Study small bodies to understand the dynamical evolution of the Solar System;
1.4. Understand the evolution of small bodies' surfaces and interiors, and the relationship to other events and processes in the Solar System, and;
1.5. Determine the source, amount, and evolution of volatiles within small bodies in the Solar System.

For Goal 2, both asteroids and comets have orbits that approach and intersect Earth's orbit, and thus have the potential to impact Earth with damaging consequences to humankind. Planetary defense refers to the combined activities undertaken to understand the hazards posed by natural objects impacting the planet and strategies for avoiding impacts or managing their aftermath. Key objectives for the goal of planetary defense are organized into five main categories:

2.1. Identify and track potentially hazardous objects;
2.2. Characterize the properties of near-Earth objects to advance both our understanding of threats posed to our planet and how Earth impacts may be prevented in the future;
2.3. Develop rigorous models to assess the risk to Earth from the wide-ranging potential impact conditions;
2.4. Develop robust mitigation approaches to address potential impactor threats, and;
2.5. Establish coordination and civil defense strategies and procedures to enable emergency response and recovery actions.

For Goal 3, the accessibility of near-Earth objects presents opportunities to enable human exploration of our Solar System, and the Martian moons represent natural outposts in the Mars system. Additionally, these small bodies may contain potentially useful resources, such as water, to further enable human exploration. In this context, small bodies represent inner Solar System destinations and a proving ground that can provide vital lessons for developing human exploration capabilities and may provide crucial resources that could enable novel exploration strategies in the future. The main objectives for human exploration of small bodies are based on key strategic knowledge gaps:

3.1. Identify and characterize human mission targets;
3.2. Understand how to work on or interact with the surfaces of small bodies;
3.3. Understand the small body environment and its potential risk/benefit to crew, systems, and operational assets, and;
3.4. Evaluate and utilize the resources provided by small bodies.

Although the three goals are treated independently, there are areas of overlap between the goals. For example, identifying and characterizing near-Earth objects has clear overlap between the objectives of all three goals. Investigating near-Earth objects provides scientific insight into the origin and evolution of small bodies in the Solar System, yields information that is critical to inform strategies to defend our planet, and supports the objectives to assess potential destinations for crewed missions and to evaluate the potentially enabling role of volatiles and other resources on such objects. The Martian moons are another example of complementary overlap between the goals, as compelling targets to fulfill objectives for both scientific and human exploration. Other examples of investigations that address objectives under more than one goal exist as well. Thus, the three goals offer complementary motivations for the investigation, characterization, and exploration of the Solar System's small bodies.

Some of the goals and objectives outlined in the SBAG Goals Document also overlap with goals and objectives identified by other planetary science communities. This overlap is viewed positively and encouraged, reflecting the interdisciplinary nature of planetary science and the presence of small bodies throughout the Solar System. Similarly, overlap and cooperation between planetary science and astrophysics communities to address the goals and objectives outlined in the SBAG Goals Document is encouraged.

While addressing multiple goals and objectives in a complementary fashion is highly worthwhile to pursue whenever possible, the number of goals or objectives addressed does not define the relative importance or priority of any investigation. Indeed, the importance of preventing the loss of human life by implementing planetary defense strategies is unquestionably of high priority. Similarly, while small bodies that do not closely approach the Earth do not factor into planetary defense or human exploration objectives, such objects present unequaled scientific opportunities for new discoveries. For example, the recent results from the Pluto system by NASA's New Horizons mission are providing paradigm-shifting, high-priority, scientific insights.

Overall, the investigation and exploration of the Solar System's numerous and diverse small bodies provide compelling opportunities to address the overarching goals of advancing our scientific understanding, defending our planet, and enabling human exploration.

SBAG Goal 1. Small Bodies, Big Science.

Investigate the Solar System's formation and evolution and advance our knowledge about the early Solar System conditions necessary for the origin of life through research and exploration uniquely enabled by small bodies.

The small bodies now present in the Solar System represent remnants of the building blocks of the planets. As such, they are our best windows into the processes that occurred during the earliest history of the Solar System. As a result of their large numbers, they also represent test particles that have survived 4.5 billion years of evolution of the Solar System, and have been influenced by many processes that have occurred during that evolution. From their orbital characteristics to their chemical compositions and their interior structures, they contain a myriad of clues to the history of the Solar System, often retaining information that the larger planets have lost. They also contain clues to the history of the biological potential of the planets, not only because they have a common pre-solar and early nebular history, but also because the bombardment of the planets by small bodies has been a significant part of the planets' histories. Small bodies are witnesses to events and conditions throughout the history of the Solar System. They include not only time capsules of water and organic materials that may have played a key role in the origin of life, but also recorders of processes ranging from the production of materials that became parts of the Solar System to the processes in the earliest days of the solar nebula to the mechanisms occurring today.

There are several different categories of "small bodies" in the Solar System, including near-Earth objects (NEO), main belt asteroids (MBA), the Martian moons, comets, Trojan asteroids, irregular moons of the outer planets, Centaurs, Kuiper belt objects (KBO), other trans-Neptunian objects (TNO), dwarf planets, dust throughout the Solar System, and meteorites and other samples of such bodies. These groups are interrelated, often without clear boundaries between the categories, and thus the scientific objectives such bodies can address, rather than the specific details of the groupings, are of the highest interest. In the text that follows, high priority scientific objectives that can be addressed by investigations of small bodies are identified, most of which apply to multiple categories of small bodies. Thus, missions and investigations that provide fundamental, rather than incremental, advances in our understanding of any of the objectives below are of the highest priority. Examples of these would be missions or investigations that deliver a significant amount of information about an objective for a previously unsampled class or subclass of objects, address an objective significantly more thoroughly, or address a significant fraction of the objectives.

Supplements that discuss these scientific objectives as they apply to particular objects or classes of objects are also provided. Small bodies categories considered in the supplements include: 1) Asteroids, remnants of terrestrial planet accretion that are found both in the main belt and as near-Earth objects; 2) Meteorites and interplanetary dust, the majority of which are remnants of small bodies that have collided with Earth, providing samples that can be analyzed with laboratory instruments; 3) Comets, bodies that outgas volatiles as they pass through the inner Solar System but that usually originate in the icy outer Solar System; 4) Phobos and Deimos, the enigmatic moons of Mars whose origin is unclear, but which may be more closely related to asteroids than to the planet they orbit; 5) Giant planet Trojans and irregular satellites; 6) Trans-Neptunian Objects and Centaurs, including Pluto and other Kuiper belt objects as well as scattered disk and inner Oort cloud objects.

Objective 1.1. Understand the census and architecture of small bodies in the Solar System.

1.1.1. Continue and enhance search programs for NEOs, MBAs, Trojans, KBOs, Centaurs and other small bodies.

A critical part of understanding the history of the small bodies in the Solar System, and hence the history of the Solar System itself, is the knowledge of exactly what is present. Size-frequency distributions, inventory, and distributions of chemical and spectral properties of astronomical objects have to be measured before they can be explained, and knowledge of the existence of these bodies is a necessary requirement. Because of their small sizes, small bodies can be inherently difficult to identify. Physical and chemical characterization, as described in objectives below, is an additional challenge. Although the bright tails of comets have been observed since antiquity, every other type of small body orbiting in the Solar System has been discovered via telescopes. Most of the discoveries have been the result of systematic search programs, whether for near-Earth objects, Kuiper belt objects, or small moons of the outer Solar System planets. Since objects in different regions of the Solar System orbit the Sun at vastly different rates, the optimal search parameters for one type of object (e.g., Kuiper belt objects) may be completely inapplicable for some other type (e.g., near-Earth objects).

1.1.2. Find and characterize new samples from small bodies through meteorites, micrometeorites, interplanetary dust, and returned samples from comets, asteroids, and other small bodies.

Laboratory analysis provides a level of detail that is inaccessible to studies using telescopes or even spacecraft. However, the level of knowledge of the Solar System that we can gain from laboratory analysis is limited by the samples available. In addition, meteorites are a highly valuable but inherently biased sample of small body material, due to the filter of atmospheric passage and the likelihood of terrestrial alteration. Hence, to fully understand the small bodies of the Solar System, samples are needed from as many different objects as can be acquired, including meteorites of as many different types as possible, micrometeorites, interplanetary dust, and samples from comets (of both silicate and icy materials), asteroids, the Martian moons, and as many other small bodies as become accessible to spacecraft technology.

Objective 1.2. Study small bodies to understand the origin of the Solar System.

1.2.1. Study the elemental, isotopic, mineralogical, and molecular composition of small bodies (through ground-based spectroscopy, spacecraft analyses, returned samples, and samples of meteoritic material) to constrain their origins.

One of the most fundamental properties of an object is its chemical composition. The chemical composition not only speaks to the processes involved in its formation (for example, determining the amount of material an object contains that would have condensed at high or low temperatures can constrain both its location of origin and the amount of mixing in the early solar nebula) but also to the possible paths its evolution may take (e.g., a body that forms with frozen volatiles may undergo processes that will not happen on an object made of more refractory material). Small bodies studies lend themselves to many techniques that are complementary and necessary for a full understanding of objects that are individually complex within diverse populations. Elemental, isotopic, and mineralogical compositions can be measured on a grain-by-grain basis for returned samples or laboratory samples of meteorites or interplanetary dust, while visible and infrared spectroscopy to determine mineralogy or molecular composition are among the most effective tools for telescopic observation. Spacecraft, meanwhile, can make direct elemental determinations with techniques like gamma-ray and X-ray spectroscopy, but without the spatial resolution of laboratory samples, or can use techniques like infrared spectroscopy to make measurements with higher spatial resolution than that of ground-based telescopes, but often at the price of poorer spectral resolution. Spacecraft-based mass spectrometers can provide molecular, elemental and even isotopic information, but are limited to the material at the location of the spacecraft. As technology improves and techniques evolve, however, in situ measurements by mass spectrometers of small body compositions via landed measurements or dust analysis could likely play an increasingly useful role.

1.2.2. Determine the timing of events in the early Solar System, using meteorites and returned samples.

Knowing the timing and duration of events is critical to understanding and constraining the processes behind them. This is true for processes as varied as chondrule formation, aqueous alteration, or impacts, each of which can be associated with specific questions that will move the field forward as they are answered. (For example, what is the relation of chondrule formation to the formation of calcium-aluminum-rich inclusions, in either time or space? How does the distribution of ages of impact events for meteorites from main belt asteroids compare to the distribution of such ages for samples from the Moon, and what does that say about the dynamical processes at work?) Different isotopic systems are sensitive to different events in the same object, so developing new techniques that provide ages, both absolute and relative, of extraterrestrial materials, can open up new lines of study.

1.2.3. Use the distribution of compositions and ages of small bodies in the Solar System to make testable predictions about observable parameters in forming planetary systems.

There has been a massive growth in our knowledge about exoplanetary systems, which has in turn helped inform studies of our own Solar System. As we seek to better link what we know about these other systems, we are left with a fundamental question: Is the Solar System typical or anomalous? One of the best ways to address this question is to determine what processes occurred and their timing and duration in the early Solar System and then compare that to what is seen in planetary systems that are currently forming around other stars. While it is difficult to observe planets around other stars, it is often easier to detect the dust and gas that small bodies generate in those systems. Measuring or estimating the timescale for gas clearance from the Solar System and how frequent collisions were enables comparisons to other systems to see if the same behavior is exhibited for the same processes.

Objective 1.3. Study small bodies to understand the dynamical evolution of the Solar System.

1.3.1. Use experimental, theoretical, and observational studies to understand the processes that alter orbits, including the Yarkovsky effect, resonances, planetary encounters, planetary migration, and other effects.

The largest NEOs are seven orders of magnitude less massive than the Moon, and comets are typically smaller still. As a result, forces that are neglected or never even considered in planetary studies may be of critical importance for the small bodies. For example, the volatile jetting that can drive changes in cometary orbits and the Yarkovsky effect that can move small objects around the inner Solar System are both processes that would be of no importance to the orbital evolution of Earth or Mars, but are major factors in the current architecture of the Solar System. On the other hand, the sheer number of small bodies allows them to be used in a statistical manner as test masses to divine the forces acting on the entire population. For instance, large-scale structures such as the distribution of orbits within the asteroid main belt, the Trojans, the trans-Neptunian region and the Oort cloud may all reflect planetary migration, to some degree. Theoretical studies provide the foundation for understanding processes that can alter small bodies' orbits, but these theoretical models need to be tested, both by experiments (either at the laboratory level or by spacecraft on actual small bodies) and by very high-precision measurements of the short-term evolution of orbits of small bodies, particularly near-Earth objects, coupled with measurements of size, shape, albedo, density, and other properties that can affect that evolution.

1.3.2. Combine theoretical and observational techniques to examine how the current distribution of small bodies evolved.

Although there are many processes that could alter the orbits of small bodies, the current architecture of the Solar System reflects one specific history. Determining what that history was, or at least determining whether a particular series of events could have led to the distribution of small bodies now observed, has important implications. The planets, including Earth, were in the same Solar System, so while many of the processes affecting small bodies would not have had such dramatic direct effects on planets' orbits, the planets were affected, both through impacts of small bodies whose orbits were greatly perturbed, and through interactions between the planets. Thus, the study of small bodies can help in the understanding of the formation and evolution of planets like Earth and Mars, or explain the enrichment of giant planet atmospheres in volatiles brought in by migrating planetesimals.

1.3.3. Search for correlations between dynamical evolution and chemical composition.

Particularly in the asteroid main belt and the trans-Neptunian region, what chemical gradients exist, and do those reflect initial conditions or subsequent evolution? While we are beginning to get isotopic information on sets of objects, most notably oxygen isotopes on meteorites and inner Solar System planets, and hydrogen isotopes on comets, it is not yet clear whether variations represent systematic trends. Any spectral trends identified by remote sensing observations could provide insight into chemical compositions throughout the Solar System.

1.3.4. Use observed orbital changes, the surface ages of small bodies determined by studies of crater density, surface morphology, spectral reflectance and other remote sensing techniques, and the cosmic-ray exposure ages of meteorites and returned samples to determine the most recent dynamical history of these objects.

Some of the effects that can alter the orbits of small bodies, most notably the Yarkovsky effect and some of the effects that occur on comets, ranging from splitting to acceleration caused by jets, can be large enough on short timescales that they can be tested for specific objects by simply following their orbits with enough precision on an extended timescale. Other effects, including planetary resonances, close encounters with planets, and some aspects of the Yarkovsky and YORP effects occur slowly or infrequently enough that they cannot be directly observed on human timescales. However, the recent orbital history of a small body is recorded on its surface, as a result of the bombardment by meteoroids and micrometeoroids and of solar and galactic charged particles, and even tidal effects (during planetary encounters). Determining the extent to which all of these secondary effects have occurred can provide constraints on the strength and nature of the orbital processes.

1.3.5. Use the observed distribution of small bodies in the Solar System to understand the possible pathways of dynamical evolution in other planetary systems.

As our knowledge of other planetary systems expands, models of the evolution of such systems are sharpened and refined. It is crucial to ask what those models would imply for the best-studied system we have, our Solar System. Just as studies of our Solar System can lead to predictions that can be tested in other planetary systems, so too can predictions based on observations from other systems be tested on our Solar System.

Objective 1.4. Understand the evolution of small bodies' surfaces and interiors, and the relationship to other events and processes in the Solar System.

1.4.1. Understand the structure of the surfaces of the small bodies, including roughness and surface compaction state, in various locations in the Solar System, and how the chemical and physical properties are modified by the space environment.

Our direct analysis of small bodies, whether via spacecraft, telescope or laboratory analysis of samples, is generally limited to material that has been at or near the surface of some body, at least in the most recent past. Therefore, it is essential to understand the mechanisms that alter the surface material, processes collectively known as "space weathering," in order to infer the properties of the underlying, unweathered, materials. However, these processes, including solar wind bombardment, micrometeorite impact, and (for icy objects) sublimation, are also worthy of study in their own right, and "space weathering" may differ on small bodies of various compositions, sizes, and distances from the Sun. Macroscopic roughness provides clues to both the structural integrity of small bodies and to their impact history. How do the regoliths of small bodies differ, and what does that tell us about their collisional and geologic history? Tenuous regoliths may build up on both icy and rocky bodies through processes such as micrometeoritic bombardment, volcanic deposition, and exogenous dust accretion. On the other hand, magnetospheric bombardment and some geologic processes will tend to increase the compaction state of the regolith.

1.4.2. Understand the overall physical properties of small bodies, including size, shape, mass, density, porosity, and spin rate.

Although most of our observations of small bodies deal with the surfaces, most of the material composing those bodies is below the surface. Properties such as microporosity abundance and distribution contain clues to the mechanisms driving the formation of primordial planetesimals. Internal differentiation (stratification) can place constraints on thermal evolution. To truly understand those bodies, we need to understand the interiors, whether the surfaces are representative of the entire bodies, and whether the interiors are homogeneous or heterogeneous, coherent or fractured, stratified (differentiated) or not. While we cannot yet directly access the interiors, their structure controls properties such as density, porosity, and gravity, some of which can be estimated from ground-based measurements (especially of binaries) or spacecraft flybys, others of which could be measured using geophysical techniques such as surface gravimetry, radar sounding, or even seismology during more extensive spacecraft interactions. Shape and gravity data, combined with spin properties, can also be used at small bodies to infer their internal structures.

1.4.3. Combine theoretical models with measurable properties to determine the evolution of the interiors of small bodies, including differentiation and melting, metamorphism, and fragmentation/reaccretion.

To understand the formation and evolution of small bodies, we need to know what the interiors of small bodies are like at present, as described in 1.4.2, but we also need to know how their interiors have evolved to their current states. Though the analysis of the interiors of current small bodies is limited, meteorites from differentiated asteroids provide samples from the interiors of larger bodies. In addition, theoretical models of the interiors of all kinds of small bodies, at scales ranging from thermal skin depths to the entire bodies, predict evolutionary paths and current structures that can be compared to the current observed states. These models require knowledge of material properties and deep understanding of the physics driving certain processes, so experimental research is also crucial.

1.4.4. Determine the current and past magnetic fields of small bodies.

Understanding the role of magnetism in the evolution of small bodies is important, to identify if magnetism arose as a result of past core dynamos during a magma ocean phase on the small bodies or from accretion of magnetized nebular material. In situ analyses of small bodies by spacecraft and laboratory analyses of remanent magnetism in meteorites and returned samples can provide insight to address this issue, with implications for understanding the differentiation of small bodies interiors.

Objective 1.5. Determine the source, amount, and evolution of volatiles within small bodies in the Solar System.

1.5.1. Measure volatiles (including, but not limited to, water, organics, other H-, C-, N-, O- and S-bearing species and noble gases) in small bodies.

Life as we know it is based on volatile elements (such as C, H, O, N, and S) and compounds (including water and organic molecules). A first-order goal is to understand the present distribution of volatiles in the Solar System. Even among objects that are basically similar, volatile contents can vary greatly. In addition, the presence of volatiles can indirectly affect seemingly unrelated properties of an object, altering minerals, causing outgassing that can affect orbits, and even contributing to resurfacing. Some meteorites are rich in hydrated materials, while others have very low volatile contents. Similarly, some asteroid spectral types have both hydrated and OH-free members. Gas-to-dust ratios and the relative abundances of volatiles such as CO and CO_2 vary widely among comets. These all provide clues to processes that occurred, but obtaining data from distinct objects and samples is needed to decipher this information within the full context of the Solar System. Volatiles can be measured easily in laboratory samples (meteorites, interplanetary dust particles and returned samples) using a variety of high-precision techniques, although contamination can complicate such measurements. Volatile compounds often have distinctive spectral signatures at a variety of wavelengths that can be used to detect them remotely, either from the ground or from spacecraft. Spacecraft can also search for volatile elements by using techniques such as neutron, X-ray, and gamma-ray measurements, as well as ultraviolet, sub-millimeter, and mass spectrometry.

1.5.2. Compare the chemical and isotopic compositions of volatiles in different groups of objects to understand the distribution of volatiles in the early Solar System.

Knowledge of the present-day distribution of volatiles in the Solar System provides a basis for understanding what volatiles were present in small bodies in the earliest Solar System and how that influenced the origin and evolution of the Solar System. Isotopic measurements are crucial, since many processes that can cause volatile loss will also cause isotopic fractionation, particularly for volatiles that end up in planetary atmospheres, including the noble gases, carbon dioxide, nitrogen and water, among others. Isotopes can be measured most precisely in the laboratory, but some volatile compounds can be readily measured remotely if they are actively outgassing. Understanding the relationship between the amount and isotopic compositions of various volatile species in various types of small bodies provides insight into the initial Solar System inventory and composition of volatiles, as well as on evolutionary processes such as hydrothermal alteration. For example, the source of Earth's water is often discussed in terms of measurements of D/H ratios from a variety of types of small bodies, made by a variety of types of instruments.

1.5.3. Determine the distribution of volatiles on individual bodies, including, where applicable, the nature and extent of seasonal volatile transport and surface-atmosphere interactions through time.

The distribution of volatiles within a body, both across the surface and with depth, contains information both about the formation of the body and about its subsequent evolution. For example, the distribution of ice with depth within a comet is a function of its orbital history as well as its original structure. Polar caps of volatiles presumably reflect volatile transport over a timescale that may be seasonal or may take much of the object's history. Small bodies in the outer Solar System that have high obliquities and/or eccentricities and sufficient mass to possess an atmosphere, such as Pluto, should exhibit seasons with volatile transport and expanding/collapsing atmospheres.

1.5.4. Determine the amounts of volatiles that different groups of small bodies can deliver to planets and moons in the Solar System.

Volatiles are crucial to the histories of planets and moons in the Solar System, but their origin on these bodies is not necessarily well understood. As just one example, the source of water on Earth remains controversial, but almost certainly involves small bodies, whether in the form of late impactors or in the planetesimals that accreted to become the Earth. Additionally, small bodies potentially contain the most pristine and least processed molecular material in our Solar System, serving as time capsules of the volatile materials that may have been provided to Earth, and the other inner planets, during the rise of life.

1.5.5. Determine the presence and state of environments on small bodies with biological potential.

There is good evidence that at least some moons of the outer planets have liquid water oceans, such as Europa and Enceladus. New evidence from the New Horizons and Dawn missions suggests the potential presence of similar subsurface liquid (water, brines, low-eutectic volatiles) on large KBOs and icy asteroids. The presence of global or regional subsurface oceans can be detected via geophysical techniques or analysis of geological features, from spacecraft flybys and orbital missions. Besides liquid water, an energy source is required for biological activity; long-lived radioisotopes may be sufficient in the case of the largest KBOs and Ceres.

SBAG Goal 1. Small Bodies, Big Science

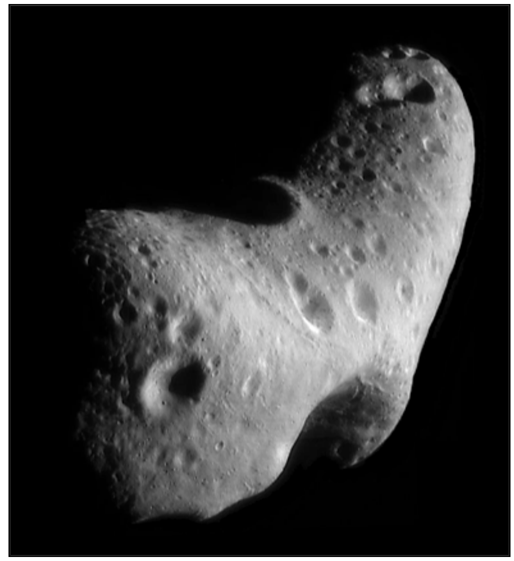
Supplements

In the supplements that follow, we discuss the scientific objectives from Goal 1 as they apply to particular objects or classes of objects, highlighting some of the major scientific questions at present but limiting the content to one page. Thus, the supplements provide a high-level overview of some of the major scientific questions but are not designed to comprehensively cover all possible scientific questions related to all small bodies. Each supplement also points out major missions, research programs, and facilities that are key to addressing the overarching scientific objectives.

We note that when addressing future missions, mission-specific discussion is explicitly limited to New Frontiers-level or larger missions identified in the Planetary Science Decadal Survey (National Research Council, 2011). Discovery missions have been extremely successful in addressing the science questions surrounding small bodies. The SBAG community strongly endorses the crucial continuation of such missions on the cadence recommended by the community in the Decadal Survey and the open competitive selection process that has resulted in novel new missions with historic accomplishments and does not wish to compromise this successful selection process by highlighting specific missions at this scale.

Similarly, when discussing telescopes, the discussion is focused on telescopes that are operated and/or funded by NASA, and discussion of future telescopes is limited to NASA projects for which first light is anticipated before 2020. However, the SBAG community recognizes the important science that other telescopes can, or will, do.

Goal 1 Supplement A: Asteroids



Eros, NASA NEAR Shoemaker

Major Science Questions

(1) What is the distribution of asteroids, both near-Earth and main belt asteroids, today, and how has material migrated from where it initially formed?
(2) What was the compositional gradient of the asteroid belt at the time of initial protoplanetary accretion, and what was the redox and thermal state/gradient of the early Solar System? How did this affect planetary formation and evolution?
(3) What was the distribution of volatiles in the early Solar System, and what role did asteroids play in the delivery of water and organics to the inner Solar System?
(4) What are the characteristics of water-rich and/or hydrated asteroids and how have the volatiles on those asteroids evolved?
(5) What are the physical properties and key processes (e.g., differentiation, hydrothermal activity, impact cratering, tectonics, regolith development, and space weathering) on asteroids and how are they modified over time?

Planetary Mission Priorities

Though several missions have flown by asteroids, and the NEAR-Shoemaker, Hayabusa, and Dawn missions have performed orbital exploration, many types of asteroids still have never been visited by spacecraft, providing numerous opportunities for scientifically compelling mission targets. Missions can provide critical data to characterize the full asteroid population and to understand the large diversity observed between these objects. The OSIRIS-REx and Hayabusa2 missions are scheduled to return samples of dark, presumably carbon-rich, asteroids in the early 2020s, addressing many key scientific objectives, though additional in situ exploration and sample return, particularly from objects not well-represented in the meteorite population, can also provide critical new scientific insights.

Research and Analysis Contributions

Research such as dynamical modeling of the early Solar System, the physics and chemistry of asteroid materials, the evolution of asteroid surfaces and interiors and the processes involved, the characterization of asteroids' properties, and numerous other topics can provide important new knowledge to address the overarching scientific objectives related to small bodies.

Key Facilities and Programs

Ground-based facilities provide a wealth of data on the asteroid population and its characteristics, including the Arecibo and Goldstone Solar System radar telescopes, the Keck and IRTF telescopes on Mauna Kea (Hawaii), Pan-STARRS, Catalina Sky Survey (CSS) and the impending Large Synoptic Survey Telescope (LSST), and well as an international network of smaller telescopes. The Minor Planet Center and the JPL NEO office record, track, and catalog the asteroid population and support planetary defense assessments. SOFIA, the Hubble Space Telescope, Spitzer Observatory, and NEOWISE also provide unique and valuable data on asteroids, as will JWST. Sustained support for laboratory studies that measure optical constants of minerals and volatiles is key to understanding the composition of asteroids.

Goal 1 Supplement B: Meteorites and Interplanetary Dust

Major Science Questions

(1) What were the conditions under which the earliest solids in the Solar System formed? Objects like chondrules and calcium-aluminum-rich inclusions (CAIs) clearly reflect high-temperature events, but what were those events, and how much mixing occurred after formation?
(2) What was the contribution of surviving pre-solar solids from distinct pre-solar environments?
(3) What was the timeline in the early Solar System? Relative to CAIs, when did chondrules form and did their formation overlap that of CAIs? 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?
(4) How did planetesimals differentiate and evolve? How did these processes differ between bodies in the early Solar System, and what processes continue to affect their evolution?
(5) What groups of meteorites or types of interplanetary dust correspond to what types of asteroids and/or comets?
(6) What kinds of organic materials are contained in which meteorites or dust? How does the abundance and distribution of organic materials depend on the history of individual objects? Were those organics synthesized within the solar nebula, or on meteorite parent bodies, or in pre-solar environments?

Planetary Mission Priorities

A key piece of information lacking from almost all meteorites is the context of the parent body, and thus missions that provide such context, through in situ measurements or sample return, are highly valuable. In addition, sample return missions provide samples that have not suffered through atmospheric entry and can provide materials that would not have survived, and hence are not represented in meteorites. Upcoming sample-return missions, such as OSIRIS-REx, Hayabusa2, and the Decadal Survey recommended New Frontiers Comet Surface Sample Return mission, are mission priorities.

GRA 06101, CV3 chondrite, ANSMET

Research and Analysis Contributions

Research on meteorites, dust, and other planetary samples, continues to progress as analytical techniques advance, enabling samples to be studied in ways not previously possible and hence providing new scientific insights even from previously well-studied specimens. Research to model and interpret measurements made on meteorites is equally important. Programs to establish and maintain expensive state-of-the-art analytical facilities are crucial to progress in meteorite research.

Key Facilities and Programs

The Antarctic Search for Meteorites (ANSMET) program is crucial to meteorite studies. The ANSMET collection represents an unbiased collection of an area, with well-documented collection circumstances, minimal contamination, and maximum accessibility to researchers worldwide. Collection programs like ANSMET are particularly crucial for identifying new groups of relatively rare meteorites. Similarly, NASA's stratospheric dust collection programs provide a unique source of material. Long-term curation is of the utmost importance to preserve the scientific value of samples available for laboratory study. The RELAB facility, with its archived spectra of numerous meteorites, provides a valuable database for drawing comparisons between meteorites and asteroids and interpreting in situ analyses.

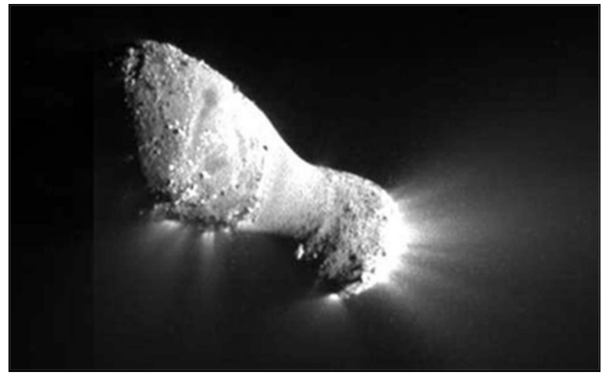
Goal 1 Supplement C: Comets

Major Science Questions

(1) Does the interior structure of a comet evolve, or is all of a comet's evolution near the surface? If the interior evolves, how does it evolve? Are the layering seen on comets a result of formation, evolution, or some combination?
(2) What is the size distribution of comets? Do the different dynamical subclasses have different distributions?
(3) What are the drivers of cometary activity? Does the nature of cometary activity depend on the activity driver?
(4) What is the life cycle of a comet as it is perturbed into the inner Solar System? For how long do comets survive once they are perturbed into the inner Solar System?
(5) What is the nature of volatiles in comets? What is the distribution of deuterium to hydrogen ratios (and other isotopic ratios) of the different comet populations?
(6) How did comets reach their present reservoirs? How do comets relate to other small body populations? Are comets original planetesimals or fragments of larger bodies? How do main belt comets relate to asteroids and "classical" comets?

Planetary Mission Priorities

While previous missions have investigated comets, there is considerable diversity within the comet population in need of further exploration. ESA's Rosetta mission has provided extensive new data about 67P/Churymov-Gerasimenko, illustrating the power of a mission that can rendezvous with a comet. The Decadal Survey identified the Comet Surface Sample Return mission as a top candidate among future New Frontiers missions and a Cryogenic Comet Sample Return as a future Flagship mission. Although the coma grains collected by the Stardust mission have provided a wealth of insights, the volume of material collected was small, and the high velocity collection technique limited the materials collected and altered some of the particles. A mission that returns a much larger sample from the surface of a comet, or that returns a cryogenic sample, would revolutionize our understanding of comets.



Comet Hartley 2, NASA EPOXI

Research and Analysis Contributions

Ongoing analysis of data already collected by both ground-based and space-based facilities is extremely important to long-term characterization of short-period comets, as well as population-wide studies of long-period comets. Additionally, the continued collection of high-quality data on new or returning comets is critical, due to the ever-evolving nature of comets and the physical and compositional diversity within the population. Research focused on interpreting cometary data through models and evolutionary processes can provide important new scientific insights.

Key Facilities and Programs

The NASA IRTF and Keck Observatories are critically important for the study of comets, as these facilities are used to determine physical and compositional properties in a large number of comets and are key for putting detailed results from individual missions into the larger population context. Radar observations with Arecibo allow the physical size and dimensions of comets to be measured, and Hubble Space Telescope observations have led to important insights into cometary activity and evolution, and JWST observations are also likely to be crucial. Publicly available archival data sets, especially those from surveys (e.g., NEAT, NEOWISE, Spitzer, SOHO), help to characterize long-term cometary behavior. SOFIA has unique access to the mid- and far-infrared wavelengths where thermal emission from the surface and dust, and molecular rotational emission, arise.

Goal 1 Supplement D: Phobos and Deimos

Major Science Questions

(1) What are the origins of Phobos and Deimos? Are they related to the spectrally similar primitive/ ultra-primitive D-type asteroids? Are they formed from re-accreted Mars basin ejecta or impactor material? If captured, where did they originate (asteroid main belt, Kuiper belt, etc.)? Do the two Martian moons have the same origin?
(2) What are the elemental and mineralogical compositions of Phobos and Deimos and how do these vary between color units? Are water and carbon present and, if so, what are their distributions with depth? How do the compositions of the Martian moons differ from one another and from Mars? Are materials from either moon represented in the meteorite collection?
(3) What are the physical and surface properties of Phobos and Deimos? What is the internal structure of each of the Martian moons? What geologic and physical processes occur (or have occurred) on the Martian moons (space weathering, impacts, tidal evolution, groove formation, etc.)? Is the redder unit of Phobos transferred material from Deimos?
(4) How do Phobos and Deimos relate to other bodies in the Solar System? Are Phobos and Deimos representative of the source bodies of water and other volatiles delivered to terrestrial planets in the early Solar System? Are surface processes on Phobos and Deimos similar to those on asteroids? How do the origin and formation of Phobos and Deimos relate to Mars?

Planetary Mission Priorities

Spacecraft focused on exploring Mars have provided much of the current data about the Martian moons, but no mission has been dedicated to exploring the Martian moons themselves. A dedicated mission to the Martian moons could greatly advance the scientific understanding of the origin and evolution of these unique bodies.

Research and Analysis Contributions

Utilizing data provided by spacecraft orbiting Mars, in particular MRO and Mars Express, the geology

Phobos, NASA Mars Reconnaissance Orbiter

and nature of the Martian moons can be investigated. Research such as modeling the different origin hypotheses or the formation of Phobos' grooves can provide scientific insight into interpreting the history of the Martian moons. Research focused on the Martian environment can constrain the processes that affect the moons, such as space weathering, dust transport, and others.

Key Facilities and Programs

Currently, the key facilities for investigating Phobos and Deimos are spacecraft orbiting Mars that occasionally observe the Martian moons, as opportunities arise, although close-range observations of Deimos are rare.

Goal 1 Supplement E: Giant Planet Trojans and Irregular Satellites

Major Science Questions

(1) Did the Jupiter Trojan asteroids originate near Jupiter's orbit or farther out in the Solar System? What can the Trojan asteroids tell us about the era of planetary migration and large-scale material transport in the Solar System?
(2) Does the diversity present in the spectral properties of Trojans result from different compositions or different maturities? If the former, do the different compositions reflect different formation locations?
(3) What is the composition of the Trojan asteroids in terms of ice and organic materials?
(4) How do Trojan asteroids compare to similar-sized objects in the asteroid main belt, Kuiper belt, and planetary satellite populations?
(5) Were all the irregular satellites of the giant planets captured from the same small body population? Were they all captured at roughly the same time? How important are the irregular satellites in terms of spreading material through the regular satellite populations of the giant planets?

Planetary Mission Priorities

There is relatively limited spacecraft data available for the irregular satellites of the outer planets, with a flyby of Phoebe by Cassini providing by far the most comprehensive coverage. The numerous other outer-planet-region small bodies are unexplored by spacecraft, and thus any mission to collect data on these objects would provide significant advances in our scientific knowledge of these small bodies. The Planetary Science Decadal Survey recommended a Trojan Tour and Rendezvous as a potential New Frontiers-level mission, and such a mission is a high priority to address key science questions. The planned Europa Flagship mission could potentially provide coverage of Jovian irregular satellites, whether those inner to Io or outward of Callisto, and there is high science value to explore such options during the development of this mission.

Research and Analysis Contributions

Observational research programs, both those that center on detailed study of individual objects and those centering on population studies, can provide key insight into the nature of outer planet region planetesimals. Dynamical studies of early Solar System history, and constraining the conditions for any model scenario, are important for understanding the history of Trojans and irregular satellites and how long they have spent in their current orbits. Modeling of the processes affecting these objects can provide key data to interpret the observational data and constrain evolutionary models.

Phoebe, NASA Cassini

Key Facilities and Programs

Access to large telescopes like Keck, and the continued existence of a cadre of both large and small telescopes, is crucial to advance our scientific understanding of these objects, given the diversity present in the Trojan and irregular satellite populations. Current and future surveys have the potential to increase the number of known Trojans or provide characterization. JWST has the potential to provide key new physical observations of these bodies.

Goal 1 Supplement F: Trans-Neptunian Objects and Centaurs

Major Science Questions

(1) What was the location in the protoplanetary nebula and what were the local conditions when trans-Neptunian objects formed? How did accretion proceed through various size regimes? What were the effects of "snow lines" of water and other volatiles? What was the extent of radial and vertical mixing in the nebula at its furthest reaches? What chemical processes occurred in the various nebular environments?
(2) What range of properties is found in the trans-Neptunian Object population? How do Kuiper belt objects compare to scattered disk objects and inner Oort cloud objects? How do classical Kuiper belt objects compare to Pluto and other resonant KBOs?
(3) How do trans-Neptunian objects evolve? What processes affect their surfaces, interiors, and atmospheres? How do binary and multiple systems form? What drives internal heating? How do internal volatile transport, compaction, differentiation, and loss of volatiles to space occur?
(4) What are the genetic relationships between trans-Neptunian objects and other small bodies populations, particularly Trojan asteroids, irregular satellites, comets and volatile-rich asteroids? What does the present-day population of Centaurs tell us about their parent population of TNOs?

Planetary Mission Priorities

In the 2003 Planetary Decadal Survey, a Kuiper belt-Pluto mission was recommended as the highest priority for a medium-, New-Frontiers-, class mission. Launched in 2006, New Horizons encountered Pluto in 2015 and is on its way for a 2019 flyby of a classical Kuiper belt object, 2014 MU69. Completion of that flyby is a high priority and will enable a preliminary understanding of the diversity and evolution of Kuiper belt objects and insights into how outer Solar System planetesimals accreted, insights not provided by the Pluto system given its sustained geological activity. Characterizing the population of trans-Neptunian objects and other small bodies in the outermost Solar System would provide new scientific insights. A future mission to an ice giant could provide valuable insight and points of comparison to TNOs by studying its irregular satellites or performing a Centaur flyby en route.

Pluto, NASA New Horizons

Research and Analysis Contributions

Research focused on modeling the observed distribution of outer Solar System small bodies, investigating the mechanical and thermal evolution of planetesimals and the mobility of volatiles, conducting laboratory studies to determine fundamental properties of cryogenic materials, and other topics can provide new insight to understand these bodies. Analysis of data from the New Horizons mission will be critical in shaping our scientific understanding of Kuiper belt objects.

Key Facilities and Programs

Because they are small and distant, trans-Neptunian objects are faint and challenging observational targets. Their study depends on access to the most capable present and future telescopes, such as Hubble, JWST, Keck, and Spitzer.

SBAG Goal 2. Defend Planet Earth

Understand the population of small bodies that may impact our planet and develop ways to defend the Earth against any potential hazards.

Our Earth is under continual cosmic bombardment. For example, the recent 2013 Chelyabinsk airburst in Russia, caused by an object estimated to be only 20 meters in diameter that exploded in the atmosphere, injured more than one thousand people by generating a shockwave that shattered windows and even collapsed the roofs of some buildings (Popova et al., 2013). In 1908, the larger Tunguska airburst of an object estimated to be roughly 30 meters in diameter caused considerably more damage, leveling more than 2,000 square kilometers of forest. (Chyba, 1993; Boslough & Crawford, 1997, 2008). If such an airburst were to happen over a major population center, significant loss of life might result. Luckily, most objects that collide with Earth are too small to pose any threat, and impacts from larger objects are infrequent, as asteroids larger than 30 meters in diameter are estimated to strike the Earth only roughly once every few centuries, and those larger than 300 meters in diameter only once per hundred thousand years, *on average*[1]. While the impact of a large object would cause catastrophic damage, the damage caused by small impactors can still be immense.

Planetary defense refers to the activities undertaken to defend Earth and human civilizations against the threats posed by natural objects impacting our planet. The objectives with regards to planetary defense can be divided into five main categories: 1) finding the potentially hazardous asteroids and comets; 2) characterizing them; 3) assessing the potential risk to Earth; 4) mitigation through deflection and/or disruption; and 5) coordination, civil defense, and emergency response to such a threat.

Objective 2.1. Identify and track potentially hazardous objects.

2.1.1. Maintain and improve ground- and space-based surveying capabilities.

The discovery and tracking of the near-Earth object (NEO) population is the first step in a viable planetary defense strategy. An object's orbit defines if, when, and how an impact will occur, and is key in defining warning times and deflection requirements. Accurate orbital information is an essential element of this process. Congress has given NASA two directions addressing NEO detection. The first, known as the Spaceguard Survey, was to detect 90% of NEOs larger than 1 km in diameter before 2008. Data from the NEOWISE space-based survey shows that this goal was reached in 2011 (Mainzer et al. 2011). The second, known as the George E. Brown goal, directed that NASA detect and track 90% of all NEOs larger than 140 m in diameter by 2020. In 2013 NASA launched its Asteroid Grand Challenge, focused on "finding all asteroid threats to human populations and knowing what to do about them." However, it is clear that current survey systems will not be able to reach the George E. Brown goal by 2020 or even within the next decade from now. Several study reports (Stokes et al. 2003; National Research Council, 2010) have found that a space mission conducted in concert with observations from a suitable ground-based telescope would be the best approach. This combination could complete the survey of objects larger than 140 meters well before 2030 and increase the number of known NEOs of all sizes by more than an order of magnitude. While the George E. Brown

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[1] It is important to recognize that Earth impact frequency statistics are very approximate and represent long-term averages at best. Earth impacts by NEOs are, in general, aperiodic events that can occur at any time.

goal is focused on 140-m and larger objects, long period comets and smaller objects also present hazards, as demonstrated by the Comet C/2013 A1 Siding Spring's near miss of Mars, and the Tunguska (~30 m) and Chelyabinsk (~20 m) airbursts. Identifying all objects that pose threats to Earth is a fundamental objective of long-term planetary defense strategies that is accomplished by continually maintaining and improving survey capabilities.

2.1.2. Identify imminent impactors, to enable wide-ranging characterization of the bodies prior to and after impact.

There have so far been two very small Earth impacts by asteroids discovered prior to atmospheric entry (2008 TC_3 and 2014 AA), and more are likely to follow in the coming decades (Jenniskens et al., 2009; Farnocchia et al. 2015). In both cases, the objects were discovered only ~20 hours prior to impact. In one case, the early recognition and announcement enabled a wide-ranging characterization of the body, both as an asteroid in space and as meteorites in the laboratory. Such events provide an opportunity to gain unique knowledge about the quantitative threats posed by impactors, with characterization while the object is still in space, during atmospheric passage, and finally in the laboratory via recovered meteorite samples. Early and timely notification of these events is imperative to fully leverage the opportunity that they provide.

Objective 2.2. Characterize the properties of near-Earth objects to advance both our understanding of the threats posed to our planet and how Earth impacts may be prevented in the future.

While an object's orbit determines if, when, and where an impact will occur, its physical characteristics play a crucial role in the potential damage it could do and in how the object would be effected by a mitigation mission. Thus, characterization of NEOs is a key objective in planetary defense strategies.

2.2.1. Determine the physical properties of the NEO population.

The NEO's mass is perhaps the most important physical characteristic to determine, but also one of the most difficult to measure. The object's mass combined with the warning time sets the deflection difficulty and is also a key parameter in determining the damage the object would inflict on Earth. Several methods are currently used to estimate mass, but the uncertainty can be as large as an order of magnitude. Understanding the porosity of the object is key to understanding the effectiveness of kinetic impactors, as well as assessing the possibility for disruption/fracture of the object during its collision with Earth. For example, porosity at some distance inside the object can dampen the shock produced by the kinetic impactor and thus limit damage to the object. The shape of the object is also an important factor that influences the effectiveness of a kinetic or nuclear deflection attempt. The tilt of the surface at the impact point affects the direction and magnitude of the delta-V vector imparted to the object by the kinetic impactor. The shape can also diminish or enhance, by more than a factor of two, the effect of a nuclear deflection attempt when compared to a spherical shape. These objects may also spin, some rather rapidly, which further complicates matters by introducing timing concerns when targeting impact at specific locations on the object's non-spherical surface. A coordinated ground- and space-based effort can characterize the physical properties of the NEO population to help develop rigorous damage and mitigation models. In situ measurements provide one of the best means to understand surface properties, mass, density, shape, porosity, and internal structure of a given asteroid. Laboratory studies of meteorites as samples of NEOs can provide unique information to further understand the physical properties of the NEO population.

Planetary radar provides unique capabilities in the physical characterization of NEOs. Radar is a powerful technique for dramatically improving our knowledge of asteroid orbits, shapes, sizes and spin states, as well as the potential presence of orbiting companions and surface structures such as boulders. Radar observations provide highly accurate astrometric measurements that significantly improve knowledge about the orbital properties of its targets, which significantly improves the ability to predict any potential future impacts. Multiple radar observations of the same object, separated over several orbital periods, can be used to measure the Yarkovsky effect (Chesley et al. 2003). The shape and the changes in the orbital properties due to Yarkovsky may together make it possible to derive mass and bulk density estimates. These are all critical properties in predicting the possibility of impact and any damage that an impact may cause. The continually improving capability of radar to reveal the character of small NEOs is exemplified by the recent bi-static observations of 2014 HQ_{124}, where a chirped X-band transmission from Goldstone was received by Arecibo using its new digital receiver. Planetary radar observations continue to be a key and unique component of the suite of characterization facilities needed to characterize the NEO population.

2.2.2. Determine the chemical properties of the NEO population.

The composition of the object is another key parameter that plays a central role in how an asteroid reacts to a mitigation attempt using a kinetic impactor or nuclear device. In particular, recent results show that the presence of high-Z (metals) or low-Z (volatiles) elements plays a substantial role. Asteroid spectra are a fundamental diagnostic tool for compositional characterization, as are chemical studies of meteorites as samples of the NEO population, and in situ measurements of asteroids' chemistry and mineralogy. How incident sunlight is scattered or absorbed by the minerals on the surface varies as a function of wavelength and these data are used to characterize and classify asteroid types and link them to samples in meteorite collections. Composition and particle size are the dominant factors that contribute to the optical and color properties of an asteroid, both of which can be indicative of the mechanical properties of the asteroid itself. Thermal infrared spectroscopy of asteroids provides information about the visual albedo and size of a given body. This knowledge is important for understanding the mineralogy and taxonomy of asteroids, the size-frequency distribution of asteroid families, and populations of asteroids. Unfortunately, thermal infrared observations from the ground are limited by atmospheric absorption to wavelength windows between 5-20 microns, making it difficult to measure the continuum spectrum around the emission peak for objects out to the main belt, motivating the need for a space-based infrared capability. Composition and size are both important parameters that need to be characterized to develop rigorous damage and mitigation models.

Objective 2.3. Develop rigorous models to assess the risk to Earth from the wide-ranging potential impact conditions.

2.3.1. Understand the effects and potential damage from an atmospheric airburst or surface impact event.

Reliable prediction of the level of direct or indirect damage caused by a NEO via an airburst or surface impact on either land or water is currently in need of development. This knowledge is a crucial consideration in formulating a proper response to possible impact threats. The foundation for our current knowledge can be found in Hills & Goda (1993), Stokes et al. (2003), and Boslough & Crawford (1997, 2008). While foundational, the first two are primarily empirical, and the latter two are reconstructive in nature (i.e., damage is predicted based on an assumed near-field energy deposition). Thus, true first principle predictive capability is lacking.

In order to improve the reliability and bound the expected damage based on the uncertainty of the properties of the NEO, there is a need to develop physics-based tools that can reliably predict the energy deposition of the break up or airburst of NEOs during atmospheric entry, as well as surface impact damage (including cratering and tsunami generation) that the objects may inflict. Considerable simulation capabilities existing in other fields may be effectively leveraged for this task, especially those supported by the Department of Energy (DoE) (blast damage) and the National Oceanic and Atmospheric Administration (NOAA) (tsunami prediction and effects). In addition to extending existing flow solvers to entry speeds applicable for NEOs (12 to 30 km/s), upgrades to tools used to propagate near-field disturbances to the surface, research on modeling of fracture/fragmentation, and multi-body and multi-phase flow is needed.

2.3.2. Understand how the impact location may influence the damage evaluation, thus guiding mitigation and civil defense strategies.

The location of impact (as well as the impact energy) is key in determining the risk and damage that would occur during an NEO impact event. For example, an ocean impact might cause tsunamis, which could affect population centers far from the source, while a similar impact into a desert, tundra or artic area might result in limited damage to population centers. Impacts in urban areas, clustered in small regions of the world, would cause disproportionate consequences, as would impacts in the vicinity of key infrastructure nodes. A composite risk assessment map should be developed to fully evaluate how impact location could influence the damage evaluation, thus guiding mitigation strategies. Such a world map would illustrate "composite risk" for a range of scenarios. It would be of use in training, planning exercises, and integrated-risk assessments, and (eventually) as an element of decision making during a real event.

2.3.3. Develop risk assessment tools that are capable of near-real time risk and damage assessment to support decision makers in the event of an imminent impact threat.

Knowledge about the orbital and physical characteristics of the NEO population and the damage they may cause through airburst or surface impact should be used to provide a set of risk assessment tools to support and aid decision makers in the event that an impact threat is discovered. These tools should be able to provide near-real time updated information on the risk assessments (impact probability, expected impact corridor, expected range of damage, risk to space assets, etc.) as knowledge improves of the approaching potentially hazardous object.

Objective 2.4. Develop robust mitigation approaches to address potential impactor threats.

2.4.1. Ensure that potential threats are addressed by early mitigation planning for potential Earth impactors.

Current impact monitoring systems at JPL and the University of Pisa continuously scan the NEO orbit catalog for potential impacts within the next 100 years, posting publicly available lists of potential impactors online (http://neo.jpl.nasa.gov/risk/, http://newton.dm.unipi.it/neodys/). This is a necessary step in responding to potential impact threats; however, there is so far no systematic examination of the potentially hazardous population to identify cases that need extra attention early for a successful deflection campaign, should one become necessary. This raises the possibility that an object already on the risk list could prove to be an intractable deflection problem due to a failure to recognize the appropriate timeline of a potential mitigation mission. It is thus important to provide active monitoring of the Potential Impactor Risk List and development of quick assessments of mitigation timelines to ensure that potential threats are addressed with appropriate resources and in a timely manner.

2.4.2. Develop and validate planetary defense approaches and missions.

At present there have been no flight missions to validate planetary defense techniques or technologies. While numerous spacecraft have performed flybys of or rendezvouses with asteroids, only the Deep Impact mission has successfully deployed an impactor. A number of studies conducted over the past decade have found the following three proposed planetary defense systems to be the top candidates for such missions: Nuclear Explosive Device (NED), Kinetic Impactor (KI), and Gravity Tractor (GT). None of these potential planetary-defense mission payloads to deflect or disrupt an NEO has ever been tested on NEOs in the space environment. Significant work is, therefore, required to appropriately characterize the capabilities of those systems, particularly the ways in which they physically couple with a NEO to transfer energy or alter momentum, and ensure robust operations during an actual emergency scenario. A planetary defense flight validation mission would be necessary prior to a technique being considered operationally ready for the execution of an actual planetary defense mission to deflect or disrupt a NEO with high reliability.

2.4.3. Have the capability to respond rapidly with characterization or mitigation missions.

The need for a planetary-defense mission aimed at deflecting or disrupting an incoming NEO may possibly arise with relatively little warning. Thus, given the importance that a NEO's specific characteristics may play in assessing the risk and devising a mitigation strategy, missions rapidly deployed to potentially hazardous NEOs to measure in situ their physical and chemical properties and structures can provide crucial information to inform decision makers. While impressive scientific missions have been sent to asteroids and comets, such missions generally require several years, usually five or six years, from mission concept development to launch. Thus, while these science missions provide future planetary-defense missions with good heritage on which to build, such missions do not provide a model of how to respond rapidly and reliably to a threatening NEO scenario. Additionally, a planetary-defense mission aimed at deflecting or disrupting an incoming NEO, possibly with relatively little warning, would not be able to tolerate any failures or schedule slips. Ways to reduce response times when it is necessary to visit or deflect a potential impactor are needed, and having small scout-class missions ready to go in order to rapidly characterize objects of interest may be a useful approach. Studies may also be conducted to identify ways to reduce response time by compressing the development and launch schedules of reconnaissance and/or mitigation missions without compromising reliability.

Objective 2.5. Establish coordination and civil defense strategies and procedures to enable emergency response and recovery actions.

2.5.1. Develop a Planetary Defense Coordination Office that will work on policy and responsibilities with respect to the threat posed by near-Earth objects.

A central Planetary Defense Coordination Office would enable efficient coordination of the policies and responsibilities for efforts related to threats posed by near-Earth objects. The 2010 NASA Advisory Council Planetary Defense Task Force, following the NASA Authorization Acts of 2005 and 2008, recommended establishing a Planetary Defense Coordination Office (https://www.whitehouse.gov/sites/default/files/microsites/ostp/ostp-letter-neos-house.pdf). More recently, similar conclusions were reached in 2014 by an audit of NASA's NEO program by the Office of Inspector General (OIG) (https://oig.nasa.gov/audits/reports/FY14/IG-14-030.pdf). Such a Planetary Defense Coordination Office would coordinate planetary defense activities across NASA, other U.S. federal agencies, foreign space agencies, and international partners. In January 2016, NASA's Planetary Defense Coordination Office (PDCO) was officially established, managed in the Planetary Science Division of NASA's Science Mission Directorate. Establishment of NASA's PDCO is a fundamental component to handling planetary defense matters, and as the PDCO develops and matures over the next few years, clear policy should be established for responsibilities with respect to the threat posed by near-Earth objects.

2.5.2. Develop interagency cooperation to coordinate responsibilities and resolve preparedness and operational issues relating to response and recovery activities on the national level in the event of a predicted or actual impact of a NEO in the US or its territories.

On February 15, 2013, the city of Chelyabinsk, Russia, experienced the effects of an atmospheric burst of an asteroid estimated at about 20 m in diameter, through a blast wave that collapsed building walls, shattered windows, and injured over 1000 people. NASA has provided NEO briefings to several interagency audiences, including FEMA. Several tabletop exercises have been conducted, both internally and in collaboration with the broader planetary defense community. FEMA and NASA are now in the process of chartering the Planetary Impact Emergency Response Working Group (PIERWG). The purpose of this group is to educate the federal agencies and other concerned organizations on the science and possible challenges in responding to impact/airburst events. For warning times shorter than a year or two, or even longer depending on the state of readiness of any mitigation options, civil defense may be the only viable option. Considerable challenges remain in establishing an efficient interagency team, and establishing appropriate communication channels between it and the planetary defense and science communities, to prepare for and respond to an asteroid impact in the US or its territories.

2.5.3. Develop efficient and appropriate responses to the threats posed by NEOs that require cooperation and joint efforts from diverse institutions across national borders.

NEOs are a global threat, and efforts to deal with an impact event may involve at least several nations. Currently, arrangements are generally ad hoc and informal, involving both government and private entities. The long intervals between events warranting response raises major concerns in maintaining attention, morale, vigilance, and preparedness for such potentially disastrous events. It is, therefore, key that a suitable international entity be organized and empowered to develop and maintain a plan for dealing with the threat posed by NEOs.

Recently, the United Nations (UN) Scientific and Technical Subcommittee within the Committee on the Peaceful Uses of Outer Space (COPUOS) assembled an action team to develop a plan for coordinating the international efforts to mitigate NEO threats. In March 2015, the action team announced the establishment of the Space Mission Planning Advisory Group (SMPAG) and the International Asteroid Warning Network (IAWN). The primary purpose of the SMPAG is to prepare for an international response to a NEO threat by facilitating exchange of information, encouraging collaborative research and mission opportunities, and providing mitigation planning activities. IAWN's purpose is to improve communication between the many actors in the worldwide effort to detect, track, and physically characterize the NEOs. Considerable challenges remain in establishing the SMPAG, IAWN, and other international units as active, vibrant entities that serve the functions they are intended to serve. There is a continued need to increase awareness within the planetary defense and science communities of these entities and their functions.

SBAG Goal 3. Enable Human Exploration.

Advance our knowledge of potential destinations for human exploration within the small body population and develop an understanding of the physical properties of these objects that would enable a sustainable human presence beyond the Earth-Moon system.

Small bodies are becoming valued destinations, not only for scientific study, but also for human exploration. These objects offer multiple opportunities for exploration and represent small worlds worthy of detailed investigation. In this context, small bodies encompass near-Earth objects (asteroids and comets) and also the Martian moons, Phobos and Deimos. They represent inner Solar System destinations and proving grounds that can provide vital lessons for developing human exploration capabilities and may provide crucial resources that greatly expand human exploration capabilities in the future. The main objectives for human exploration are based on closing key strategic knowledge gaps (SKGs) that are focused on: 1) mission target identification; 2) small body proximity and surface interaction; 3) identification of small body environment hazards and/or benefits; and, 4) small body resource utilization.

Objective 3.1: Identify and characterize human mission targets.

Small bodies provide a rich diversity and large number of potential human mission targets that can accommodate a broad range of objectives. Identification of specific human mission targets within the small body population involves several stages: (1) Evaluation of astrodynamical accessibility (required mission change-in-velocity (Δv), required mission duration, available launch dates, etc.) and identification of accessible targets; (2) Evaluation of relevant physical characteristics (e.g., composition, shape, size, rotation rate, presence of secondary or tertiary bodies, etc.); and (3) Evaluation of relevant human factors (e.g., health and safety in the small body's environment, effects of space environment on crew during the mission duration, etc.). Small bodies exhibit a wide range of physical characteristics, such as rotation rate, orientation of spin axis, and the possible presence of secondary or tertiary objects. These quantities can offer advantages, challenges, or pose hazards to spacecraft and crew (Table 3.1). Therefore, a set of criteria defining what ranges of parameter values are acceptable for human missions must be established. Criteria on the suitability of a given small body as a human destination based on its physical properties and human factors will evolve over time as planned crew infrastructure and space exploration architectures evolve. However, astrodynamical accessibility criteria can generally be evaluated independently of physical characteristics and are taken as the starting point for identifying small bodies that are candidate targets for human missions. Many of these small bodies are highly accessible and offer opportunities that have significant advantages over other destinations (Figure 3.1). Maximizing the population of small bodies from which human mission targets can be selected is most effectively achieved by conducting a space-based survey.

3.1.1. Discover and identify asteroids that are astrodynamically accessible from Earth.

NASA's Near-Earth Object Human Space Flight Accessible Targets Study (NHATS) is an ongoing project (Barbee et al., 2013) with the goal of monitoring the growing known Near-Earth Object (NEO) population for mission accessibility. The list of known NHATS-compliant NEOs is maintained at http://neo.jpl.nasa.gov/nhats/, and is automatically updated daily as new NEOs are discovered and orbit estimates for already discovered NEOs are updated. However, the NHATS list of potential mission targets should not be interpreted as a complete list of viable NEOs for an actual human exploration mission. As new observations of these objects are obtained, the NEO orbits are updated, which can change the viable mission targets and their mission parameters. Physical characteristics, discussed further below, can also significantly restrict the total number of suitable targets. Additionally, tighter constraints on other criteria, such as round-trip mission duration or Δv, can shrink the number of targets considerably (See Tables 1 and 2 in Barbee et al, 2013). Because of these factors, it is beneficial to continue to discover new asteroids to increase the pool of potential targets. However, ground-based visible light surveys are biased against objects with orbits interior to Earth's and others having long synodic periods or low albedos. This limits the number of NEOs that may be found in highly accessible orbits. The most effective method for finding these objects is via a dedicated space-based NEO survey system. Therefore the most important aspect to this objective is to:

- **Identify NEOs in Earth-like orbits.** What are the numbers of highly accessible targets with Earth-like orbits? What is their size frequency and albedo distribution?

Enabling Precursor Measurements: Deploy a dedicated space-based asset in an orbit optimized for the discovery of objects in near-Earth space.

Applied Exploration Science Research: Continue the NHATs project. Discover and characterize more NHATs-compliant targets.

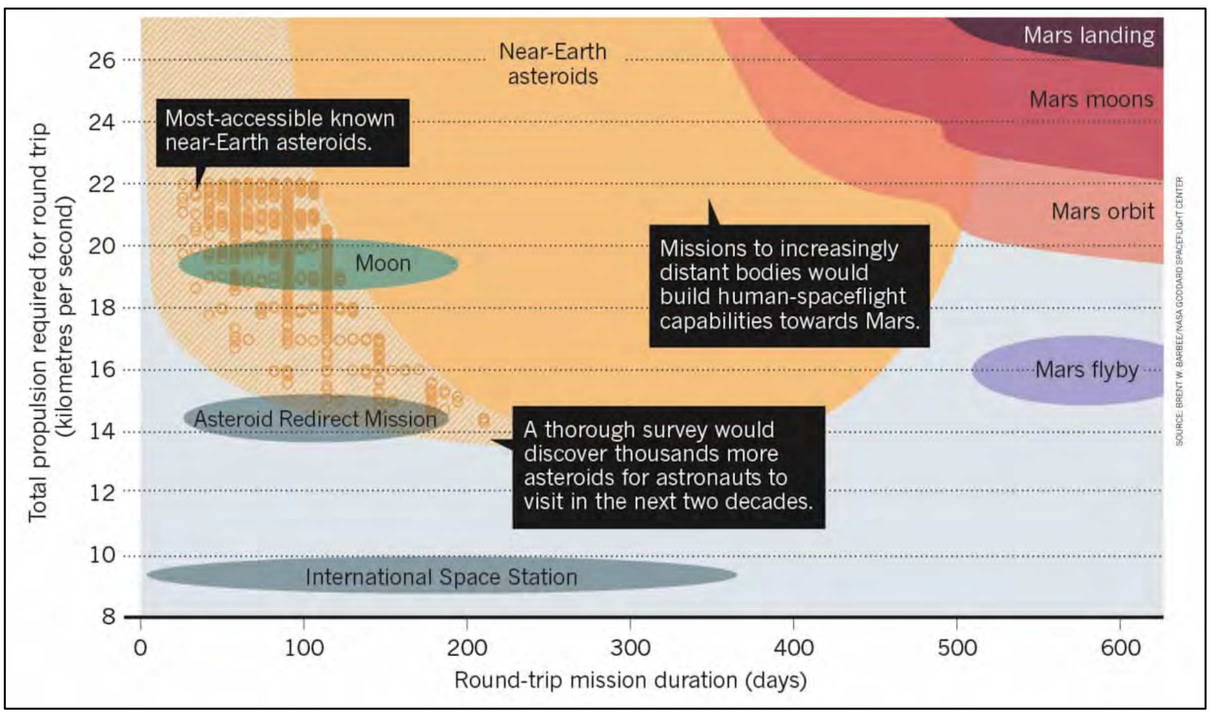

Figure 3.1. *A mission to a near-Earth object can require less propulsion and a shorter mission duration than a human mission to any other celestial target. Less than 1% of the estimated population of most accessible NEOs are currently known (yellow circles), but a dedicated space-based survey (filling in the yellow-hatched region) would reveal abundant NEO stepping-stone opportunities as a gateway for interplanetary exploration.*

Table 3.1: Important physical characteristics relevant to human exploration of small bodies.

Rotation rate	
Small bodies can have rotation periods ranging from tens of hours (Pravec and Harris, 2000) to less than a minute (Miles, 2008). Fast rotators present several challenges: • Humans experience physiological difficulties when in a fast-rotating frame • A quickly spinning object may be near its cohesional strength limit, any perturbation may dislodge debris • Synchronizing spacecraft with a fast-rotating object could be operationally expensive (e.g., propellant use) *Objects with rotation periods greater than two hours are preferable.*	*Measurement techniques* • Lightcurve observations • Radar observations
Rotation axis	
Although most objects have a stable rotation axis, some undergo a "tumbling" motion in which the rotation axis changes chaotically over time (e.g., Takahashi et al., 2013). • Objects with non-principal axis rotation (i.e., tumbling) may present operational challenges *Stable rotation axis, or predictable rotation axis alignment, is preferable.*	*Measurement techniques* • Radar observations • Lightcurve observations
Presence of satellites	
Roughly 16% of near-Earth objects larger than 200 m across have a satellite (Margot et al. 2002). Two triple systems (NEOs with two satellites) have also been observed. • The presence of a moon allows for the determination of small body mass, and therefore density. Prior knowledge of these properties could greatly simplify mission planning and reduce mission risk. • Small body moons are often tidally locked, and therefore often spin at the same rate as the primary body. They could be attractive mission targets in their own right. • A moon could also present an operations hazard and, in that situation, would need to be avoided. *The area around a target should be searched for satellites.*	*Measurement techniques* • Radar observations • High-resolution imaging • Lightcurve observations
Cohesion and stability	
Some small bodies are monoliths, solid pieces of rock or metal. Others are loosely bound aggregations of dust and rock, and are called "rubble-piles" (e.g. Love and Ahrens, 1996; Fujiwara et al., 2006). *Advance knowledge of the type of gravitational and physical environment would assist mission planning.*	*Measurement techniques* • Radar shape modeling • Lightcurve modeling • Shape and rotation rate. • Thermophysical modeling can provide some constraints regarding whether the surface is coated in regolith or dust
Mass	
Small body mass is a highly valuable quantity for mission planning. It is also difficult to measure.	*Measurement techniques* • Can be derived from a natural satellite orbit • Flyby/rendezvous mission • Some constraints from combining Yarkovsky measurements and thermophysical modeling

3.1.2. Expand the knowledge of asteroid physical characteristics.

High accessibility of an NEO alone does not necessarily make it an attractive target; it is also important to know the NEO's physical characteristics. For example, some asteroids have rotation periods of less than a minute (Miles, 2008), which would prove challenging for crewed and robotic missions. There are many techniques that may be used in concert to characterize a small body's physical properties (Table 3.1). Ground-based radar observations can dramatically improve the accuracy of a NEO's orbit, and these data can help constrain the object's composition (e.g., metal, Shepard et al., 2008). In addition, NEO diameters and spin rates can be determined using radar data (Benner et al., 2015). Lightcurve measurements can also determine spin rate and aspect ratios (Warner et al., 2009), and can be obtained for objects much more distant than ground-based radar is capable of imaging. High-resolution radar images can be inverted (and, in some cases, combined with lightcurves) to produce estimates of NEO shapes and spin axes. Such shapes and rotational information can give insights about surface stability and structure. Radar images can also be used to identify the presence of satellites (Benner et al., 2015). Spectroscopy can constrain surface composition and infrared measurements can constrain asteroid surface reflectivity (albedo), and size (Mainzer et al., 2015). Thermophysical modeling combines many of these datasets (size, shape, spin axis) to produce an average surface thermal inertia of a body, which helps constrain characteristics, such as surface roughness and regolith thickness (Delbo et al., 2015). However, only a small fraction of NEOs have been studied with any one of these techniques, and an even smaller fraction has been studied using multiple techniques. By filling in these knowledge gaps, we would have a better sense of the type of environment that a mission to a NEO would encounter. This would allow us to better prepare for such a mission, well before a specific target is chosen. More objects need to be studied with the aforementioned techniques in order to:

- **Understand the physical characteristics of small bodies.** What types of compositions are present among the NEO population? What is the range of NEO shapes and rotation states? What are their surfaces like? Do they have companions? What objects have characteristics that would make them good targets?
- **Identify the best methods to characterize NEOs for human exploration.** What techniques, or combinations of techniques, give the most relevant data needed to inform human missions?

Enabling Precursor Measurements: Investigate potential target NEOs in situ via robotic spacecraft.

Applied Exploration Science Research: Continue characterization of small bodies using established ground-based techniques. Support a program of telescopic investigations using the full range of remote techniques that follows up NEO discoveries with in-depth characterization of physical properties. Model NEOs using ground-based and spacecraft data. Develop an improved database for NEO physical characterization data.

Objective 3.2. Understand how to work on or interact with the surfaces of small bodies.

Detailed knowledge of the surface properties of small bodies, in addition to the physical and mechanical properties of the near surface and interior, must be obtained prior to conducting human exploration missions on these objects. Such data are crucial for planning science (optimizing tools and techniques) and resource utilization activities that will be conducted at small body targets (e.g., NEOs, Phobos, and Deimos). A robotic precursor mission is the ideal method to obtain this information. The knowledge needed for small body interaction depends upon the degree of interaction that is planned. The following categories describe the different levels of interaction in increasing order of complexity: 1) Approach; 2) Transient Contact; and 3) Extensive surface interaction (i.e., anchoring).

3.2.1. Characterize the environment for extended proximity operations.

A prerequisite to interacting with the surface of a small body is to approach it safely. The small body's rotation state must be understood and the rotation rate(s) must be within acceptable limits for human and spacecraft interaction. The rotation period must be predictable across timescales greater than the duration of the mission so that the dynamic and lighting environments can be accounted for in operations planning. The orbits and rotation states of any satellites/particulates must be known, and safe approach and departure corridors identified. That requires using the spacecraft instruments to search for natural satellites as the spacecraft makes its gradual approach to the small body. In addition, the crew is highly likely to conduct a variety of operations over an extended period of time, necessitating accurate positional information with respect to the small body's surface and any other objects in the vicinity (e.g., natural objects). This would involve detailed knowledge of the gravitational field of the object, as well as precision spacecraft navigation that utilizes both radiometric tracking and optical navigation. Many small bodies are not spherical objects and often have irregular shapes and mass concentrations. The gravitational field, albeit weak, will not be uniform. Therefore the following are important to this particular objective:

- **Understand the rotation state of the object.** How fast is the object spinning? Is this a non-principal axis rotator? How does the axis of rotation and the spin rate affect the operations that can be conducted by the crew?
- **Identify natural satellites or particulates in proximity to the object.** Does the object have a companion? Are there particulates in close proximity to the object? If so, where are they with respect to the object as a function of time?
- **Map the shape and surface topography of the object.** What is the shape of the object? Are there any surface features that are potential hazards to proximity operations or future surface operations? Are there certain areas of the small body more conducive for human exploration than others?
- **Map the gravitational field of the object.** Is the gravity field uniform? Are there variations with rotation? Do stable orbits exist and where are they located?

<u>Enabling Precursor Measurements:</u> Obtain in situ high-resolution imagery of the specific target in question to determine rotation state and presence of co-orbitals/natural satellites. Determine shape model and conduct topographic mapping for surface feature characterization and identification. Perform detailed radio science mapping of the target's mass distribution and gravity field.

<u>Applied Exploration Science Research:</u> Obtain ground-based optical and radar observations of select targets. Model lightcurves for rotation rate, mode, and shape inversions. Develop models

of co-orbital/natural satellite generation and dynamical evolution. Model small body orbital dynamics.

3.2.2. Characterize the small body's surface physical characteristics.

The first approach to the surface of a small body for a human mission might be conducted cautiously via telepresence using a small robotic vehicle, or with a piloted vehicle utilizing test-firings of braking and attitude-control thrusters to confirm findings from the previously deployed precursor spacecraft. Simple transient contact is the safest and easiest interaction, a touch-and-go that requires only forces directed away from the surface. A push on the surface itself can provide that force, while thruster firings could probe surface characteristics and assess any tendency of the spacecraft to kick up particulates. Spacecraft, robotic vehicles, sample collectors, or spacewalkers can interact with the surface in this manner. During the brief contact with the surface, robotic vehicles and crew may be able to collect a variety of samples or deploy equipment. Designing and deploying these assets will depend on advance knowledge of the target's physical characteristics. Therefore data are required in order to:

- **Understand the surface response to mechanical interaction or spacecraft thrusters.** What is the surface like in terms of regolith? Is there a significant amount of particulate material? How "dusty" is the surface? What is the cohesion of the particles? How easily are they liberated from the surface?
- **Understand the local gravity environment.** Are there any areas on the body that have near zero or negative local gravity (including rotational effects)? Will this help or hinder touch and go operations?
- **Determine the composition.** What is the composition of the object? Does the object have more than one type of composition? Is the composition detrimental, benign, or beneficial for human interaction?

<u>Enabling Precursor Measurements:</u> Obtain in situ high-resolution imagery and spectroscopy (e.g., optical, infrared, X-ray, and gamma-ray) of the specific target to determine surface morphology, composition, and particle size distribution. Conduct detailed radio science mapping of the target's gravity field locally with respect to rotation. Investigate the surface via small payloads or direct contact (e.g., OSIRIS-REx and Hayabusa2 spacecraft missions).

<u>Applied Exploration Science Research:</u> Model small body surface compositions and regolith dynamics. Conduct experiments with regolith simulants under micro-gravity conditions; ISS experiments with meteoritic materials. Analyze meteoritic materials for potentially hazardous compounds and the determination of acceptable exposure limits.

3.2.3. Characterize the small body's near-surface geotechnical and mechanical properties.

Touchdown of a spacecraft to the surface of a small body can be challenging, but it has been demonstrated several times (e.g., NEAR-Shoemaker, Hayabusa, Rosetta's Philae lander). However, attaching a spacecraft or instrument to the surface for extended operations and interactions requires knowledge of the mechanical properties of the near surface. This is required to plan for a spacewalking astronaut as well, whether moving on pre-deployed lines or nets, articulated booms or arms attached to spacecraft, or on small maneuverable spacecraft. Designing the systems required for extended periods of operation at the surface and possibly while anchored to the subsurface will depend on detailed knowledge of the target's geotechnical, mechanical, and internal properties. Specific questions concerning the small body's properties must be addressed in order to:

- **Understand how to anchor spacecraft, astronauts, and instruments to the small body surface.** What forces are required for anchoring? Are there particular techniques that are beneficial for human exploration? Is there a need to anchor in all instances? Can anchors be deployed in regolith or at boulders?
- **Understand how to translate across the small body surface.** What are the best ways to translate for an astronaut on EVA vs. a spacecraft? Will regolith help or hinder this activity? Are there preferred locations/conditions for translation?
- **Understand how to collect samples from the small body.** What types of samples can be collected? How difficult is it to collect sub-surface samples or samples from a boulder?
- **Understand how to minimize contamination of work sites, equipment, and habitat.** What are the possible contaminants and modes of contamination? What protocols need to be implemented? How are suits and equipment cleaned/protected?

<u>Enabling Precursor Measurements:</u> Conduct remote sensing and in situ investigations of the surface via a variety of payloads. Payloads that measure surface and subsurface properties such as particle size and shape distribution, internal structure, cohesion, compaction, shear, porosity, etc. would be optimal.

<u>Applied Exploration Science Research:</u> Model small body surface and sub-surface properties, regolith depth and evolution. Conduct experiments in regolith simulants under micro-gravity conditions; ISS experiments on meteoritic materials.

<u>Objective 3.3. Understand the small body environment and its potential risk/benefit to crew, systems, and operational assets.</u>

Understanding the nature of the small body environment and the associated risks and potential benefits to human explorers is important to facilitate future exploration and proximity operations at/near small bodies, such as NEOs or the Martian moons. In general, unknowns relating to human operations risk factors for the small body environment can be most effectively addressed through one or several robotic precursor missions. These "known unknowns" can be placed into three categories: 1) Understand the small body particulate environment; 2) Understand the ionizing radiation environment at small body surfaces, and; 3) Understand the internal structure and tectonic stability of small bodies.

3.3.1. Characterize the small body particulate environment.

Dust in the small body environment may act as both a hazard and a nuisance, especially given the known physical, chemical, cohesive, and electrostatic properties of dust in a microgravity environment. There are also potential health and equipment integrity concerns relating to dust particle morphology (e.g., sharp and jagged shapes). Dust, if defined by electrostatically dominated particles, can actually be much larger than equivalent terrestrial or lunar dust. Characterizing the nature, sources, and behavior of dust in the small body environment is therefore a key mid-term (within the next 5-10 years) objective that will feed into future hardware trades. Of particular importance is to:

- **Understand the expected particulate environment from surface disturbance due to micrometeoroid impacts and human operations.** How much material is ejected into space, and how does it behave following ejection? Does the potential for adhesion to spacecraft and/or astronauts pose a substantial risk?
- **Understand particle levitation following surface disturbances.** How long do any levitated particles remain in close proximity to the object? What are their levitated lifetimes? What are their expected orbital paths?
- **Understand possible dust and gas emission via sublimation from volatile-rich objects.** What is the potential for emissions from volatile-rich objects and does this pose a nuisance or risk to crew and spacecraft at or near the surface of the small body?
- **Understand the population of the particulate torus associated with Phobos and Deimos.** What are the particle densities and distributions within this region? Do these particles present any hazard?

Enabling Precursor Measurements: Obtain in situ high-phase angle, long-duration imaging (including during and following impact-induced surface disturbance) of small bodies. Utilize a dust environment detector similar to those carried by legacy ALSEP experiment packages and (more recently) the LADEE spacecraft.

Applied Exploration Science Research: Conduct modeling and impact laboratory experiments, ISS experiments, mitigation experiments, and strategy development.

3.3.2. Characterize the small body radiation environment.

This includes both secondary charged particles and neutrons produced in the regolith. Ameliorating radiation effects through hardware and mission design choices lessens the need to use pharmacological remediation strategies for human exploration. In addition, small body surfaces may afford a measure of radiation shielding that could provide benefit during long duration exploration missions. The CRaTER instrument on the Lunar Reconnaissance Orbiter (LRO) continues to provide new information about the radiation environment in cis-lunar space that may prove relevant to understanding the unique aspects of the small body environment (i.e., NEOs, Phobos, and Deimos) that require further measurements, which include the following:

- **Understand local effects on the plasma and electrostatic environment from solar flare activity.** The concern is that solar flares may lead to enhanced dust levitation or other hazards/nuisances.
- **Understand small body surfaces for providing shielding and as a source of secondary radiation.** Small body materials may provide substantial shielding from the deep space radiation environment. In addition, small body surfaces may have materials that enhance radiation production during solar flares.

Enabling Precursor Measurements: Instruments with analogous capabilities to LRO's CRaTER or another type of tissue equivalent dosimeter should be flown to a target object to characterize the small body radiation environment. Of particular importance is measuring the degree of shielding provided by a small body during a solar flare and from galactic cosmic rays, though guaranteeing such a measurement may require a long-duration mission.

Applied Exploration Science Research: Conduct laboratory modeling of small body radiation environment; perform data mining of XGRS/GRS instruments from Dawn, Hayabusa, and NEAR; extrapolate from LRO-CRaTER dataset and model secondary radiation using lunar examples. Existing radiation models need to be upgraded to fully accommodate planetary regoliths (including small bodies) as a source of secondary radiation, as well as potential interactions between the small body and the spacecraft.

3.3.3. Characterize the local and global internal stability of small bodies.

Considering the diversity of small bodies, a "one-size-fits-all" model for small body interiors is largely infeasible: every small body is different. However, broad categories of internal structure can be developed, given enough information. This raises the importance of adequate precursor mission characterization to understand the internal structure and stability of small body surfaces. Of particular concerns are the potential effects of human operations that interact with the surface, which could cause mass wasting. Understanding the stability of small bodies is thus also important to enable small body in situ resource utilization. Given the evidence that many smaller objects appear to be rotating at or near breakup speeds, it is certainly possible that relatively small surface disturbances could lead to major reorganization or shedding of material. Therefore it is important to:

- **Understand the local structural stability of small bodies.** Limited direct astronaut interactions and remote interactions (via telepresence), such as geologic sample collection or the emplacement of subsurface seismic instrumentation, could potentially cause mass movement of material.
- **Understand the global structural stability of small bodies.** Larger-scale activities and exploration efforts that interact extensively with (for example) small body regolith could have unpredictable consequences, and these must be more fully understood.

Enabling Precursor Measurements: Obtain measurements of rotation rates of target asteroids to better than 1% precision; conduct in situ measurement of mass using radio science; measure and model the volume and shape using LIDAR; conduct analysis of local gradients in the local, non-radial, gravity field via high resolution imaging, perform in situ measurements of cohesion and shear strength using imaging and geotechnical experiments; and deploy an in situ seismometer or seismometer network. Emerging radar and muon tomography measurements could offer a potential pathway to map asteroid internal structure prior to surface interactions, and their use should be more fully explored.

Applied Exploration Science Research: Conduct long-term light curve and radar observations to study small body physical properties as they relate to internal structure. Conduct analog research on ISS to determine cohesion and shear strength in an appropriately weak gravity field, particularly for cohesion and shear strength tests and validating granular physics models. Forthcoming LEO cubesat experiments (e.g., AOSAT I), as well as microgravity flights and suborbital experiments, might also provide useful information.

Objective 3.4. Evaluate and utilize the resources provided by small bodies.

Human activity in the Solar System is necessarily limited because of the historical requirement that all propellant, shielding, equipment, life-support, supplies, and vehicles for any given activity be transported from the surface of the Earth at great expense. To expand human activity beyond cis-lunar space, the cost must be dramatically reduced. The identification, recovery, and utilization of resources from small bodies represent an opportunity to achieve this goal and should be a central objective for future space exploration agencies and entities. The promise of small body in situ resource utilization (ISRU) has been discussed and written about for decades. Achieving the ISRU objectives will provide the information required to make an informed technical assessment of the cost-effectiveness and practicality of small body ISRU for the support of human spaceflight. Carbonaceous chondrites contain ~1-20% water by mass, and in some cases up to 40% recoverable HCNO volatiles. Water can be broken down and used as propellant directly or in a thermal propulsion system as reaction mass. Water from NEOs has also long been contemplated for life-support and radiation shielding. Phobos and Deimos, which may be captured asteroids, have also long been considered as sources of propellant in Mars orbit. Recent spectral studies of Phobos show possible, but not definitive, signs of hydrated minerals on its surface (Fraeman et al., 2014). Therefore, a more detailed examination of the Martian moons' surface and interior compositions is necessary to determine their ISRU potential. In addition, meteorite compositions suggest that some NEOs may be potential sources for valuable platinum-group metals, as well as other materials that could be useful for construction in space.

3.4.1. Identify and characterize NEOs with low albedos and accessible round trip Δv from Low-Earth Orbit.

Continuing astronomical surveys are vital in order to identify many potential asteroid targets, because some will be unsuitable (e.g. due to rotation rates) and the long synodic period means that only a small fraction will be accessible in any given year. It is insufficient to merely discover small bodies; they must also be characterized to determine whether they may be resource-rich. This can be determined via combinations of albedo measurement and spectral analysis. The most effective way to conduct this survey would be to deploy a dedicated space-based NEO survey asset in an orbit away from Earth's vicinity. This would help to:

- **Understand NEO characteristics.** What is the orbital element distribution of potential resource-containing objects? Does this vary with size? What are their rotational characteristics? What is the population of such objects that are binaries?

Enabling Precursor Measurements: Deploy a dedicated space-based NEO survey system optimized for detecting low-albedo objects and also capable of determining rotation rates. Conduct detailed in situ investigation of potential resource-rich NEOs via proximity measurements from suitably instrumented spacecraft.

Applied Exploration Science Research: Conduct systematic ground-based and space-based spectroscopic, radiometric, and rotational characterization of all known NEOs satisfying Δv and magnitude (brightness) constraints. Obtain radar characterization data as much as possible.

3.4.2. Identify dormant comets within the NEO population and determine the state and depth of water ice within them.

Since the identification of 4015 Wilson-Harrington (1979 VA) as P/Wilson-Harrington in the 1990s, it has been known that some fraction of the NEO population is composed of dormant comets. Water ice may exist within the interiors of such objects at a depth of only a few meters. Other volatiles (e.g., ammonia) may also be present that could be of value as resources for human space activities. Identification may be achieved via albedo measurement and spectroscopy, coupled with orbital evolution analysis and monitoring for intermittent outgassing activity. Specific identification of volatile species and the quantitative abundance of these species require in situ study. Therefore it is important to:

- **Understand the NEO comet population.** What is the orbital element distribution and size distribution of comets within the NEO population? What fraction of NEOs are cometary objects?
- **Understand the mechanical properties of the near surface of NEO comets.** Are there hard and soft layers in addition to apparent loose aggregates (e.g., as has been found on the Rosetta target comet 67P)?
- **Understand the depth and distribution of volatile species (e.g., water ice, organics, etc.) in the comet interior.** How accessible are these species within a comet? To what depth are they buried?

Enabling Precursor Measurements: Rendezvous with a potential NEO comet to characterize its interior and potential extent of volatile species using a combination of remote and in situ investigations. In addition, perform investigations to determine the mechanical and geotechnical properties of the object's near surface material(s).

Applied Exploration Science Research: Conduct systematic ground-based and space-based spectroscopic and radiometric study of known NEOs to identify those with cometary characteristics. Perform long-term monitoring and Earth-based radar characterization of suspected cometary candidates.

3.4.3. Characterize the surface and near-surface composition and geotechnical properties of a NEO resource target.

While we have hand samples from some NEOs in our collections of meteorites, the bulk properties of NEOs are relatively unconstrained. For example, the spectral properties obtained of the asteroid 2008 TC_3 did not predict the geochemical diversity within and across the Almahata Sitta meteorites collected following the asteroid's encounter with Earth. This raises questions about the extent to which a meteorite sample may be representative of the bulk properties of its parent NEO. This needs to be resolved via in situ surface and subsurface studies of a target NEO in addition to characterization of its geotechnical properties. Such activities would help to:

- **Understand the genetic relationship between carbonaceous meteorites and carbonaceous NEOs**. Can any carbonaceous meteorites be linked to specific NEOs? Do the volatile contents measured in carbonaceous meteorites reflect the abundances available on carbonaceous NEOs?

- **Understand compositional and mechanical homogeneity and heterogeneity over small and large spatial scales and with depth.** Do meteorites provide insights into the potential compositional diversity and mechanical properties of target surfaces? Do they provide insights into the potential range of such properties? Can compositional and mechanical homogeneity/heterogeneity of NEOs be correlated with the taxonomic diversity of material within their dynamical vicinity either in the NEO population or main-belt source region?
- **Understand space-weathering effects on carbonaceous NEOs (asteroids and comets)**. In addition to the production of nanophase irons, what other effects to non-silicic carbonaceous materials might occur that would change its chemistry?

<u>Enabling Precursor Measurements</u>: Perform detailed mapping of spectral, thermal, and radar properties of NEOs by spacecraft. Collect and analyze multiple surface and core samples. Conduct detailed probing of large-scale interior structures that may contain volatile species. Return samples from carbonaceous NEO targets.

<u>Applied Exploration Science Research</u>: Conduct systematic ground-based and space-based spectroscopic studies of NEOs and laboratory studies of carbonaceous meteorites along with dynamical studies to create links between meteorites and NEOs. Search for variations in radar reflectivity of carbonaceous NEOs that are radar imaged.

3.4.4. Characterize the surface and near-surface composition and geotechnical properties of Phobos and Deimos.

Phobos and Deimos have long been suggested as sources of in-space propellant for missions to land astronauts on Mars and provide fuel for then returning them to cis-lunar space. However, while there is some evidence to suggest that there may be hydrated species present, there is no conclusive evidence from surface spectroscopic observations to confirm the presence of abundant resources (i.e., water, volatiles, etc.). The current data are inconclusive due to the lack of a dedicated robotic mission to investigate these Martian moons. The potential value of such resources motivates a spacecraft mission focused on the Martian moons to determine their subsurface compositions with depth and also characterize their geotechnical properties. Resolving the question of whether resources are present on the Martian moons could have significant implications for any program to send humans to Mars, since the presence or absence of useful propellant resources would substantially change the design, cost, and timeline of missions that involve sending astronauts to Mars. Hence in order to evaluate the resource potential of the Martian moons, additional data are required to:

- **Understand the volatile inventory of the Martian moons**. Do the Martian moons contain volatiles at a sufficient abundance to serve as resources for human exploration? Is recoverable volatile material available near their surfaces or in their interiors?
- **Understand compositional and mechanical homogeneity and heterogeneity over small and large spatial scales with depth.** What is the surface and interior composition of Phobos and Deimos at different locations and depths? What are the physical properties of the regolith and subsurface? Are the Martian moons contaminated by materials from the surface of Mars, and, if so, to what extent and what depth?

Enabling Precursor Measurements: Conduct detailed mapping of spectral, thermal, and radar properties of Phobos and Deimos by spacecraft. Collect and analyze multiple surface and core samples. Probe large-scale interior structures that may contain volatile species. Return samples from one or both moons.

Applied Exploration Science Research: Perform laboratory studies of carbonaceous meteorites and identify similar features in the spectra from Phobos and Deimos that may be indicative of volatile species on the surface of the Martian moons.

3.4.5. Test hardware to excavate and mechanically process small body material (or suitable simulant) and convert it into propellant in a microgravity and vacuum environment.

There are many unknowns about the bulk mechanical properties of NEO material and what would be required to excavate and process it into material suitable for further processing (which might be thermal, mechanical, and/or chemical) into useful resource materials. There may be systematic differences between the material properties of NEO comets, carbonaceous asteroids, and Phobos and Deimos. This is further complicated by unknowns associated with the execution of mechanical and chemical processes in microgravity conditions under vacuum. The best platform for developing and testing these processes in a small body-like environment and making them robust may be the International Space Station. Therefore it would be prudent to:

- **Understand the range of chemical and mechanical properties of a potential small body sample.** Might there be metal and/or “hard” rock? Are there volatiles that would contaminate extracted water? What are the different chemical states of extractable water?
- **Understand how to process material in microgravity conditions under vacuum.** What must be done to prevent loss of material from simple mechanical handling? How are water and other materials extracted and segregated? How is the extracted material purified and separated into desired components?

Enabling Precursor Measurements: Conduct rudimentary materials handling and processing at the surface of a small body via a deployed ISRU technology demonstration experiment.

Applied Exploration Science Research: Assess carbonaceous meteorite samples for heterogeneity. Conduct experiments testing mechanical and chemical processes on the ISS.

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