SMALL BODIES EXPLORATION IN THE NEXT 35 YEARS.
T. D. Swindle[1] and The SBAG Steering Committee (N. Chabot (APL), B. Barbee (NASA GSFC), J. Bauer (JPL), B. Bierhaus (Lockheed Martin), D. Britt (UCF), J. Castillo-Rogez (JPL), P. Chodas (JPL), L. Feaga (U. Maryland), C. Hartzell (U. Maryland), C. Mercer (NASA Glenn), A. Stickle (APL)), [1]LPL, University of Arizona, tswindle@lpl.arizona.edu.

In the last 35 years, our knowledge of small bodies has increased by orders of magnitude, from roughly 2000 numbered asteroids to nearly 500,000, from one known trans-Neptunian object (Pluto) to 2300, from ~2000 meteorites to more than 55,000, from no samples from any specific small body to samples returned from a comet's coma (Stardust) and an asteroid's regolith (Hayabusa) with two more spacecraft on their way to return asteroidal samples, from no spacecraft images of small bodies other than Martian moons to flyby, rendezvous, and/or landing missions to a dozen comets and asteroids plus Pluto. What will we achieve in the next 35 years? A good place to start is to look at the goals that the Small Bodies Assessment Group (SBAG) has defined for the exploration of small bodies, and consider where we are poised to make progress.

The SBAG Goals Document [1] identifies three overarching, high-level goals pertaining to the Solar System's small bodies, 1) utilizing the Solar System's small bodies as the scientific probes of the Solar System's formation and evolution, 2) defending planet Earth against the potential hazard that the impact of comets or asteroids represents, and 3) taking advantage of the unique properties of the small bodies in the inner Solar System to enable human exploration.

Science: 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. The high priority scientific objectives identified by SBAG are to understand the census and architecture of small bodies in the Solar System, to study small bodies to understand the origin of the Solar System and the dynamical evolution of the Solar System, to understand the evolution of small bodies' surfaces and interiors, and the relationship to other events and processes in the Solar System, and to determine the source, amount, and evolution of volatiles within small bodies in the Solar System. There are numerous ways in which the science related to small bodies is likely to advance.

We are likely to achieve much greater knowledge of the population of TNOs and the Oort Cloud (which should become accessible at least to telescopic observations), enabling us to address questions not just of the origin of the known planets, but also of whether other large, perhaps even planet-sized, objects exist in the cold outer reaches of the Solar System. The New Horizons spacecraft has demonstrated that Pluto is a much more active body than had been expected, and it will be flying by another TNO in its extended mission. Centaurs are an as of yet unexplored category of small bodies that exhibit evidence of cometary activity, ring systems, and binaries, and may serve as a mid-stage sample of the effects of solar exposure on TNOs. Whether we send spacecraft to explore the outer reaches of the Solar System may depend on development of effective communications and propulsion systems.

Already, we have two spacecraft, Hayabusa-2 and OSIRIS-REx, en route to return samples from (primitive?) carbonaceous asteroids. The study of that material, plus refractory and sub-surface cryogenic material returned from a cometary nucleus, will give us a much greater knowledge of what kinds of materials were available to provide volatiles to the terrestrial planets, and how closely the origin of water and/or organic material on Earth may be tied to different types of small bodies that we can study today. In addition, Ceres may be the most accessible ocean world.

Increased scrutiny of, and, in particular, sample return from, from Mars' moons can address the long-standing puzzle of their origin. That question has fundamental implications for the dynamical environment in the vicinity of Mars, which, in turn, is wrapped up in the origin and evolution of the entire inner Solar System.

We are only beginning to study Jupiter's Trojan asteroids. They are highlighted as a New Frontiers mission target in the most recent Decadal Survey, with a history waiting to be deciphered.

Meteorite investigations have led to dramatic increases in our understanding of the nature and timing of accretion and differentiation of small bodies within the early Solar System. Future analytical advances and the continued discovery of rare meteorite types will lead to new insights during the next 35 years. The study of more asteroids (both in situ and via sample return) will lead to more specific constraints for Earth-based laboratory studies of meteorites.

Planetary defense: Some small bodies have orbits that approach and intersect Earth's orbit, and thus have the potential to impact Earth, possibly with damaging consequences to humankind. Planetary defense refers to the combined activities undertaken to understand the hazards posed by near-Earth objects impacting our planet and develop strategies for avoiding impacts or managing their aftermath. In 2005, Congress directed NASA to detect 90% of all near-Earth objects (NEOs) larger than 140 m in diameter by 2020 [2]. Current surveys are inadequate for achieving this goal, even by 2050. But, a combination of space-based and next-generation ground-based systems could complete the survey well before 2030, as well as increase the number of detected NEOs of all sizes by more than an order of magnitude. Several multi-meter objects are likely to be found days before impacting Earth. Although probably too small to be hazardous, observing these objects as they impact, and possibly collecting resulting meteorites, will provide unique opportunities to study asteroid strengths and link asteroid classes with meteorite physical properties.

In order to develop robust mitigation approaches to address potential impactor threats, it will be important to validate these techniques through demonstration missions. It is likely that we will launch a Kinetic Impactor demonstration mission in order to assess the importance of ejecta in the momentum transfer of the mission. Deflection demonstrations of other techniques, such as gravity tractor, ion beam deflection, and laser ablation would be appropriate to ensure robust operations during an actual emergency scenario.

Enabling human exploration: The accessibility of NEOs, and in particular, near-Earth asteroids (NEAs), presents opportunities to enable human exploration of our Solar System, and the Martian moons represent natural outposts in the Mars system. NEAs may contain resources, such as water, that human explorers could utilize, thereby enabling exploration missions that would otherwise require the launch of significantly more material from Earth. In this context, NEAs are inner Solar System destinations in their own right, as well as a proving ground at which we can learn vital lessons pertinent to the extension of human exploration capabilities to more distant destinations. Moreover, the crucial resources offered by small bodies may enable novel exploration strategies in the future. The main objectives for human exploration of small bodies are based on key strategic knowledge gaps, including identification and characterization of potential human mission targets; understanding how to work on or interact with the surfaces of small bodies; understanding the small body environment and its potential risks and benefits to crew, systems, and operational assets; and evaluation and utilization of the resources provided by small bodies.

The techniques that will make it possible to identify hazardous NEOs for planetary defense purposes will also vastly increase the number of known NEOs that are potential exploration targets for humans. This is because many of the most hazardous NEOs occupy rather Earth-like orbits, which also makes them the most accessible objects outside the Earth-Moon system. NASA monitors the accessibility of the NEAs via the automated Near-Earth Object Human Space Flight Accessible Targets Study (NHATS) system. At the time of this writing, 1,894 of the known NEAs have been identified by the NHATS system as being more round-trip accessible than Mars, and 70 are more round-trip accessible than low lunar orbit.

Missions like Hayabusa, Hayabusa-2, OSIRIS-REx, and Rosetta are spending more and more time working and taking measurements in the vicinity of asteroids and comets. As a result, we are learning, and will continue to learn, about the physics of operations in the vicinity of small bodies. Large increases in knowledge are likely to occur when humans are actually present. Although SBAG's human exploration objectives are tied to closing the existing Strategic Knowledge Gaps, there is much intrinsic science about small body environments that astronauts will uncover.

Phobos and Deimos are easier to access with a crewed spacecraft than the surface of Mars, and lack the planetary protection issues posed by Mars, so they are likely to play key roles in the human exploration of Mars, either for precursor missions or as outposts for teleoperated activities on the Martian surface.

At present, exploration missions rely on bringing all needed supplies, from fuel to shielding to building materials (for space stations) to food (for crewed missions). There are NEOs that can probably satisfy many of these needs, and there are now private companies with the stated goal of mining asteroids. If any of these companies are successful, it will not only revolutionize travel beyond Earth orbit (for both crewed and robotic spacecraft), but there are also a host of scientifically interesting properties about the structure and interiors of asteroids that will be learned through these activities. Furthermore, the amount of material that would be moved around the inner Solar System by a commercial mining operation will mean that far greater quantities of material will be available for scientific study than would ever be acquired based solely on a science justification.

References:

[1] http://www.lpi.usra.edu/sbag/goals/ (2016). [2] George E. Brown Act (2005) H.R. 1022 (109th Congress). [3] http://neo.jpl.nasa.gov/nhats/