THE SMALL SATELLITES OF THE SOLAR SYSTEM: A WHITE PAPER COMMISSIONED BY SBAG FOR THE 2011-2020 PLANETARY DECADAL SURVEY

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Deimos

Abstract

The small satellites are a diverse group of objects offering insights into the early formation of the Solar System and its collisional history. Many of these objects are believed to be captured asteroids or Kuiper Belt Objects: a spacecraft mission to them would thus yield information on an object that came from elsewhere in the Solar System. Objects that came from the same reservoir as the small outer irregular satellites may have brought both pre-biotic material and volatiles such as water to the inner Solar System. Flagship and New Frontiers class missions should plan trajectories and arrival times to capture spectroscopic and imaging observations of small satellites. The EJSM should make every effort to accomplish a targeted flyby of an outer irregular satellite of Jupiter. It is also important to support ground-based and Earth-orbiting observations of these objects, and to have more extensive laboratory measurements of candidate surface materials. We place highest priority on a New Frontiers class mission to Phobos and Deimos, the satellites of Mars. A sample return from this mission would include material from a D-type object and possibly the Martian surface.

I. The small satellites: An overview

The small satellites are a diverse group offering insights into the formation of planetary systems, the primordial conditions and current architecture of gaseous planet-systems, and the migration of small bodies within the Solar System. Many of these satellites are thought to have been asteroids or Kuiper Belt Objects (KBOs) that were captured around the giant planets by a dynamical mechanism (see reviews by Jewitt and Haghighipour 2007; Nicholson et al. 2008), although some orbit within the gaps of Saturn's rings and around their edges (see Table 1). Many of these moons show evidence of violent pasts: one is in chaotic rotation (Hyperion) and others are heavily cratered. They are compositionally diverse, ranging from low-albedo C-type objects such as Phoebe to bright icy objects such as the inner satellites of Saturn. Captured bodies offer windows into the physical conditions of remote regions of the Solar System. The scope of this paper includes both distant captured satellites and small inner satellites. All of these objects are irregular in shape and are ~200km or smaller in radius.

Table 1 – A summary of the small satellites of the Solar System

Planet	Satellite or group	#	Distance from primary (km)	Radii (km)	Comments
Mars	Phobos		9376	11.6	Captured C or D asteroids; each one is unique
	Deimos		23458	6.2	
Jupiter	Inner moons	4	128,000-222,000	4-83	Amalthea largest
	Outer moons	54	7,284,000-28,455,000	0.5-85	Many retrograde; breakup-families
Saturn	Inner moons	13	133,580-377,420	11-89	"Shepherds",coorbitals, Lagrangians
	Hyperion		1,500,880	135	Chaotic rotation
	Phoebe		12,947,780	107	Captured KBO?
	Outer moons	37	11,110,000-25,146,000	2-20	Most retrograde
Uranus	Inner moons	13	49,000-97,736	36-68	Prograde
	Outer moons	9	4,282,900-20,430,000	9-75	Retrograde (except one)
Neptune	Inner moons	6	48,227-117,646	33-210	Prograde
	Nereid		5,513,818	170	
	Outer moons	5	16,611,000-49,285,000	20-31	3 retrograde
Pluto	Nix		48,709	46	Similar to Charon in composition
	Hydra		64,749	61	

Sources: JPL Horizons; Weaver et al., 2006.

Because the distantly orbiting irregular satellites exhibit collision probabilities typically four orders of magnitude higher than those found among main belt asteroids, they are laboratories for collisional processes and formation scenarios for the outer planets. Nesvorny et al. (2007) argued that outer irregular satellite capture may have taken place during giant planet close encounters within the so-called Nice model framework (Tsiganis et al. 2005; Morbidelli et al., 2005). But the satellites' shallow Size-Frequency Distribution (SFD), which is markedly different from that of the Trojans, either argues against the Nice model or it indicates these bodies are the most collisionally-processed objects in the Solar System. The reservoirs from which the outer irregular satellites were captured may now be largely empty due to early scattering.

The small outer satellites also exhibit an ecological link to the rest of the Solar System. The dust – and larger pieces - from these collisions may provide material to alter the surfaces of major satellites such as Callisto, Iapetus, and the Uranian satellites (Buratti et al. 2005; Bottke et al., 2009). The inner moons may provide material to the ring systems of the giant planets, and they in turn are coated with ring material. Both prebiotic compounds – the elusive dark material of the outer Solar System – and volatiles are brought into the inner solar system by comets, which share common origins with many of the small satellites. Finally, Charon and its kin Nix and Hydra, may have dynamical origins analogous to the Moon (Canup and Asphaug, 2001). Some of the satellites orbit at such great distances from their primaries that they seem to be the Oort clouds of the giant planets. Perhaps the two populations even had the same source location, namely the primordial trans-planetary disk that was once located just beyond the orbits of the giant planets.

Although a dedicated future mission to a specific satellite is justified only for Phobos and Deimos, it is important to design any upcoming missions to capture opportunities to scrutinize these objects. An example of this planning was afforded by Cassini's flyby of Phoebe, which gave the first view of what was probably once a KBO (Johnson and Lunine, 2005).

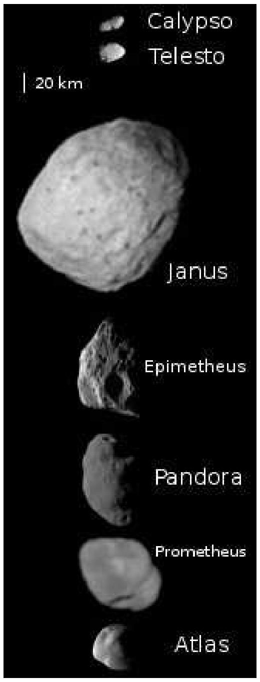

Figure 1. *Some of the small, inner satellites of Saturn.*

II. Top-Level Scientific Questions

The driving questions regarding small satellite research and missions include:

- What is the compositional and dynamical relationship between the small satellites and other bodies in the Solar System, including the outer main asteroid belt, Hildas, Jupiter and Neptune Trojans, KBOs (including the scattered disk), Centaurs, comets (including those from the Oort cloud), and the main satellite systems? Why do some small satellites appear to resemble P/D-type asteroids and others resemble C-type asteroids (e.g., Phoebe)? Is this an intrinsic difference, an evolutionary difference, or some combination of the two?

- What determines the densities of the satellites? Specifically, why is the density of many so low? Are they rubble piles of loosely accreted material or material of a satellite that was broken apart and reaccreted?

- What mechanism captured the outer irregular satellites, and how does this mechanism constrain planet formation processes in the outer solar system? Were they captured from accretion regions near the giant planets during planet formation, or are they refugees from a massive primordial disk of comets that may have existed beyond the orbits of Uranus/Neptune? Can outer irregular satellites be used to verify or rule out the predictions made by Solar System formation scenarios?

- What are the interior composition and structure of Phobos and Deimos? Is there a dust ring associated with them, and can it reveal their composition?

- How has the high number of collisions shaped the outer irregular satellites (e.g., can we use these bodies to probe the nature of icy planetesimals?)

● How have the outer small satellites bombarded the main satellite systems? What is their role in the chronology of the main satellites as derived through crater counts?

● What is the relationship between the inner small moons of Saturn and its rings? Are they compositionally related, and do the moons determine the morphology of the rings?

III. Required Research and Research Facilities

To address the above questions, a better understanding of the moons' composition, dynamical states (rotation periods and pole positions), phase curves, and sizes is needed. Because of their distance and small size, the study these moons has been largely limited to broadband photometric analyses in the visible and near-infrared, leading to classifications based on colors. Advancements in our knowledge of their composition, including identification of specific volatiles, organics, and minerals, will be made through the acquisition of near-infrared spectra. Currently only 10-m class telescopes are sufficiently equipped to provide these spectra, though additional observing time at facilities such as Keck would be helpful. Facilities including 10-m class telescopes and larger (e.g. TMT) need to be equipped with proper instrumentation for modest resolution spectroscopy and have dedicated time for planetary observations so that a statistically significant number of satellites can be thoroughly studied. It is especially important to continue to discover the outer satellites, to increase the pool of mission targets (Section V).

Observations with ALMA will provide size measurements and albedos for all known outer irregular satellites, and JWST will provide thermal infrared measurements, following on the advances made by Spitzer. WISE should have completed its mission by mid-2010, having observed several of the largest irregulars (down to a few km) at 3-25 µm. Especially valuable will be ground-based campaigns of spacecraft targets to understand the rotational phase at the time of encounter, dynamics, albedo, and over-all context for planned mission measurements.

Also key are focused laboratory studies. Perhaps the most serious drawback to the identification of specific compounds on these moons (and other objects) is the lack of laboratory comparison spectra. NASA should support laboratory work to gather the spectra of volatiles, organics, and minerals at the temperatures appropriate to the outer solar system. The effects of grain size, temperature, and viewing geometry should be studied. In addition, laboratory work on the mechanical properties of ices should also be supported. Support should be made available to have optical constants and other data online and easily accessible to investigators.

IV. Technology Needs

The needed technology developments for missions to small satellites include propulsion technologies, telecommunication technologies, sensing technologies, guidance navigation and control technologies (GN&C), sampling technologies, and autonomy technology.

Propulsion technologies: Rendezvous missions, or multiple asteroid tours will frequently require low-thrust propulsion. There is heritage from DS1 and Dawn, but further investment in mission design and planning systems is required, and for missions that target objects beyond Mars, it's likely that nuclear-, as opposed to solar-electric propulsion will be required, which will require substantial investment.

Telecommunications technologies: Depending on the range to a prospective target, science return may be limited by bandwidth. Solutions to this limitation may include extending the life of the DSN 70m network, creating an alternative small-element very-large-array network, or optical com, all of which will require substantial technology investment.

Sensing Technologies: For distant deep space targets, fast wide-field imagers will be required. For all missions, LIDAR or RADAR ranging capability will be needed, and/or structured light systems. Gimbaling of sensors, especially imagers, can greatly enhance science return.

Autonomous GN&C: All missions making contact and many orbiting missions may require onboard autonomous guidance navigation and control. Deep Impact and DS1 used such a system, but for small body proximity operations this system requires extension. Contact itself will challenge the spacecraft GN&C, inducing difficult-to-predict torques, and necessitating possibly complex ascent control strategies to insure departure without appendage contact.

Autonomous Planning Sequencing and Commanding: Having onboard command systems capable of dynamically reacting to conditions sensed onboard will enhance science return and reduce operational costs, and provide for greater mission reliability. Orbital conditions around small bodies are difficult to manage and providing an onboard environment that can maintain the science objectives reactively will be necessary.

Sampling mechanisms: The wide spectrum of possible sampling mechanisms include sticky-pads, brush-wheel samplers, corers, surface sample ejectors, and explosives. They all require to some degree mechanical and actuation support, including active deployment arms, release mechanisms, or capture baskets/containers. All of these methods will also require transfer mechanisms to move the samples to in situ analysis instruments or to Earth return capsules.

With the exception of some of the Autonomous GN&C systems, instruments, and Sequence and Commanding technologies, few of these developments are likely to be needed by the manned program. On the other hand, most of these technologies are applicable across a wide spectrum of robotic mission categories, including missions to NEOs, Asteroids, Dwarf Planets, Centaurs and KBOs as well as Small Irregular Satellites.

V. Major Mission Priorities

Although studies of small satellites are not yet mature enough to warrant a dedicated Flagship Class Mission over the next decade, they are arguably as interesting as the Trojan asteroids and thus could potentially warrant their own New Frontier mission in the follow-up to this Decadal Survey. In addition, a New Frontier sample return mission to Phobos and Deimos should be a high priority. Beyond this, the small satellites are superb secondary targets for big missions en route to other locations. The design of instruments and spacecraft should encompass the goals for small satellites, as long as cost and schedule permit. Any Mars mission should include the study of Phobos and Deimos. Whenever possible, spacecraft trajectories, arrival times, and instrument turn-on should be planned to capture the following measurements:

A. Flagship missions: A mission to Titan, Enceladus, or another target in the Saturnian system should include observations during SOI of Phoebe, and if possible one or more of the outermost satellites. The required observations include visible and IR spectroscopy to determine their composition, and imaging to determine size, crater frequency, and geologic history. Another important area is the dynamical interaction between the small inner satellites, Saturn's rings, and the major satellites. Propellers, wakes, and gaps in the rings are all defined by small satellites orbiting in the ring regions: wherever possible high resolution imaging and spectroscopy of these objects should be planned. ***EJSM should target at least one outer irregular satellite of Jupiter, and it should obtain observations of Amalthea and the other inner satellites.***

B. New Frontiers Missions: If at all possible, a mission to Jupiter, Neptune (and Triton), or Uranus should include imaging and visible and infrared spectroscopic observations of the outermost satellites and objects such as Amalthea, Puck, and Nereid. These satellites will provide detailed views of the collisional environment in the outer Solar System, and compositional determinations will reveal kinships with KBOs and outer Main Belt asteroids. Detailed UV, IR and imaging obsevations of Nix and Hydra are already in the New Horizons encounter plan, and support should be forthcoming for the study of any newly discovered moons of Pluto.

Although sample returns from Phobos and Deimos were proposed as Discovery Missions (Britt et al., 2003; Pieters et al., 2009) cost considerations currently place these missions in the New Frontiers class. These moons offer a window to study primitive materials that accreted in the outer part of the main asteroid belt, outside the terrestrial planet-forming zone. They are also deep in the Martian gravity well and thus have been accumulating ejecta from impacts on Mars. It has been suggested that up to 10% of Demios' regolith may be Martian material (Britt, 2003; although Gladman 2007 has criticized this notion). Deimos is energetically more accessible than Phobos and has a remarkably smooth surface, rendering it "safe" for sampling operations.

A sample return mission to Phobos and Deimos is our only high priority, dedicated mission for the Decadal Survey. This mission would bring back to Earth D-type material as well as possible Martian material from the Noachian period since that is the period of maximum impact flux and of large basin formation. The main goals of the sample analysis would be to: study the geochemistry in the region of the outer asteroid belt and Jupiter; study prebiotic material in the Solar System; search for isotopic biomarkers on early Mars; determine the compositional diversity and history of the Martian crust, including dating the era of heavy bombardment. Martian ejecta accreted on Deimos would probably include crustal and upper mantle material from the period of early differentiation as well as later samples when Mars had a more dense atmosphere and possible surface water. The mission could bring back up to several kilograms of material. The payload would consist of a camera for context of the samples and global characterization, navigation, and sample site selection; a radar-altimeter for closed-loop approach maneuvering, and a wide-angle camera to document the sampling process.

A Russian sample return mission called Phobos-Grunt (Phobos soil) is planned for launch later this year. The lander will continue to operate on the surface for up to a year. This spacecraft has a range of instruments and the Planetary Society Living Interplanetary Flight Experiment which will transport 10 types of microorganisms on the spacecraft.

Another goal of either mission would be to study the dust environment around the satellites and the possibility of a dust torus associated with the moons (Soter, 1971; Dubinin et al., 1990; Baumgärtel et al., 1996; Showalter, et al., 2006).

A separate white paper on Deimos and Phobos is being submitted (Scott Murchie et al.). Larger missions to use Phobos and Deimos as bases for human exploration of Mars and beyond have been proposed, but they are beyond the scope of this white paper.

VI. Discovery Science Goals

There are no currently high priority Discovery class missions to small satellites. The only (remote) possibility would be a mission to a newly discovered satellite of Venus or Mercury.

VII. Balancing Priorities

- ***Recommendations on the optimum balance among small, medium, and large missions and research programs.***

Because our only high priority mission is a New Frontiers sample return mission to Phobos and Deimos, we have no specific recommendations. In general, there should be more Discovery missions because they are faster, can cover more targets, and are less expensive.

A robust research program on large telescopes, both earth-based and orbital, is necessary to advance small satellite science. Current laboratory studies are piecemeal, a consequence of funding serendipitous proposals from scientists with a somewhat narrow focus. To provide a basis to prepare for and interpret data from missions, NASA needs a comprehensive set of spectra over a range of temperatures, grain sizes, geometry, and wavelengths and to that end should establish a facility with such an open-ended goal.

- ***Recommendations on the balance among small, medium, and large missions and research programs when choices must be made across categories of programs because of limited funding.***

Flagship missions should not gobble up smaller missions, as the latter represent more goals, opportunities (especially for young scientists), and targets. Small missions also mean a faster turnaround, which enables building upon the technology developed for the prior. Instead the Flagships should be delayed or descoped to the “science floor”. Missions should never eliminate or tax research programs, as basic research is the fountainhead of new mission concepts.

- ***What should be done if cost overruns begin to expand a mission budget to the point where other programs will be affected (negatively).***

When costs are overrun, missions should be descoped by taking actions such as deleting instruments and putting members of the science team “on ice.” Each mission proposal should include a "science floor” so missions can be descoped. Delays should be avoided, as they end up costing more in the long run and disrupt other programs (although an AO can be delayed). Missions should never be canceled, because taken together they represent a carefully thought plan of priorities by NASA.

- ***How could/should new discoveries affect your priorities?***

Undoubtedly new satellites will be discovered, but they will not affect priorities because they are not driving missions. The goals relating to irregular satellites for Flagship and New Frontier Missions are pretty generic. The highest priority for a New Frontiers mission - to Phobos and Deimos - will not change. In the unlikely event a satellite was found around Mercury or Venus, it would warrant a Discovery mission.

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