SBAG Special Action Team Report:

ARM Connections to Priority Small Body Science and Exploration Goals

Submitted September 26, 2016

I. Introduction

I.A. *Charge:*

In a memo dated June 28, 2016, Dr. Michele Gates, Program Director of the NASA Asteroid Redirect Mission (ARM), requested that the Small Bodies Assessment Group (SBAG) form a Special Action Team (SAT) to help:

"1) Identify any connections between the science objectives for small bodies as identified in the planetary decadal survey report "Vision and Voyages for Planetary Science in the Decade 2013-2022" and those stated as ARM objectives.

2) Identify any small body Strategic Knowledge Gaps (SKGs) that could be addressed, in whole or in part, by the activities conducted during the ARM."

I.B. *Membership:*

The Special Action Team consisted of five individuals with applicable expertise. Members were:

- Timothy Swindle, University of Arizona, Chair
  Current Chair of the SBAG Steering Committee
- Carolyn Ernst, Johns Hopkins University Applied Physics Laboratory
  Member of the ARM FAST
- Christine Hartzell, University of Maryland
  Member of the SBAG Steering Committee and of the ARM FAST
- Andrew Rivkin, Johns Hopkins University Applied Physics Laboratory
  Chair of the SBAG SKG SAT
- Mark Sykes, Planetary Science Institute
  Former Chair of the SBAG Steering Committee, member of the SBAG SKG SAT

I.C. *Crucial documents:*

- Asteroid Redirect Mission (ARM) Formulation Assessment and Support Team (FAST) Final Report, NASA/TM-2016-219011
- Final Report: NEO/Phobos/Deimos Strategic Knowledge Gaps Special Action Team, SBAG SKG SAT, http://www.lpi.usra.edu/sbag/documents/ (2012); SKGs are given in Table A.1
- Vision and Voyages for Planetary Science in the Decade 2013-2022, Committee on the Planetary Science Decadal Survey, Space Studies Board, Division on Engineering and Physical Sciences, published by the National Academies Press, Washington DC (2011); the Specific Objectives for small bodies are given in Table A.2.

I.D: *Caveats:*

The SAT notes there are several caveats that should be kept in mind:

- The small bodies SKGs were established in 2012 based on the then-current goal of sending a crewed mission to a roughly 30-meter asteroid in heliocentric orbit. The Asteroid Redirect Crewed Mission (ARCM), in particular, may address SKGs for subsequent crewed missions to other destinations, but this report will be limited to the small bodies SKGs.

- There is far more science that can be done than is encompassed by the objectives for primitive bodies from the Decadal Survey ("Visions and Voyages for Planetary Science in the Decade 2013-2022"). Although virtually any visit to an object that has not been visited before will result in serendipitous science, this report is limited to science that addresses stated Decadal Survey objectives. This report should not be seen as contradicting or superseding findings by SBAG in 2013-2016, or at a later date.

- ARM was designed as a human exploration mission, not a science-driven mission. As a result, while it will achieve some Decadal Survey objectives for small body science it will likely not do so as efficiently or completely as investigations primarily designed for meeting those science objectives per se.

- The FAST report contains a discussion of potential science investigations available by expanding the instrument suite on ARRM. In keeping with this spirit, the SAT makes note of science that could be achieved by adding instruments and analysis to the baseline mission.

II. Strategic Knowledge Gaps addressed by ARM

The robotic component of the ARM mission (ARRM) will require a series of operations (e.g. maneuvering near an asteroid, landing, extracting a boulder, departing the surface, and returning to the Earth-Moon system) that will contribute to many of the SKGs either directly or as a consequence of the mission design. The local structural stability of the asteroid, for instance, will be observed whether or not it is intended. Similarly, while quantitative evaluation of the dust-related SKGs will require additional identified instrumentation, the act of landing and block extraction will likely cause surface disruption and dust generation similar to an EVA.

Many of the SKGs as originally conceived were expected to require a visit to the specific astronaut target in order to be closed. If the boulder is "the target", or if astronauts return to 2008 EV5 (or whichever target is visited by ARRM if not 2008 EV5) later, these SKGs would be closed. If astronauts visit a different asteroid in its heliocentric orbit, these SKGs might be considered partly closed or not addressed.

Given these assumptions, the SAT identified three SKGs that would be addressed by the baseline robotic mission, and two that would be addressed by the crewed mission. An additional eight SKGs could be addressed by an enhanced ARM with additional payload, additional human activity, post-mission analysis, or samples returned from the boulder. Considering both the baseline and an enhanced mission, 13 SKGs could be addressed (of the 27 not linked specifically to Phobos or Deimos), some of them in multiple ways.

The five SKGs that ARM (ARRM+ARCM) will contribute to in its baseline configuration are:

1. Round trip limitations due to radiation exposure.
2. Non-contact close proximity operations for detailed surface exploration and surveys.
3. Geotechnical properties of small body surfaces (although there are many additional measurements that could enhance the way this is addressed)
4. Local structural stability based on remote measurements.
5. Knowledge of how to excavate/collect NEO material to be processed.

A more detailed description of the linkages between ARM and the SKGs (including the relevance of additional instruments or measurements) is given in Table 1.

Table 1. Strategic Knowledge Gaps that can be addressed by ARM

SKG ID	Description	Rationale	Contribute or Close?	ARRM, ARCM, or ARM?	Contingent on additional payload/additional human activity/post-mission analysis
I-A-1	Round trip limitations due to radiation exposure.	ARCM will bring astronauts to regions of reduced magnetic shielding, thereby increasing their exposure to radiation. The total duration of radiation exposure (~20days) will be too small to close the SKG.	Contribute	ARCM	N
II-A-1	Biological effects of Small body surface dust.	If dust remains on the surface of the boulder in DRO, the ARCM mission could contribute to the understanding of this SKG.	Contribute	ARCM	Y
II-B-1	Mechanical/electrical effects of SB surface dust.	With the appropriate sensors, the existence of dust and the determination of its mechanical/electrical effects on equipment during the boulder collection process should be determinable.	Contribute	ARRM	Y
II-D-2	Non-contact close proximity operations for detailed surface exploration and surveys.	ARRM will increase NASA's experience with asteroid proximity operations.	Contribute	ARRM	N
III-A-4	Possible particulate environment in the asteroid exosphere due to charged particle levitation following surface disturbances	If the appropriate sensors and mission operations are implemented, the uncertainty on this SKG could be reduced during the detailed mapping phase and if the near surface environment is inspected during/after boulder detachment.	Contribute	ARRM	Y
III-B-2	Small body surfaces as a source of radiation.	If the appropriate sensors and mission operations are implemented, ARRM could contribute to this SKG during its surface operations.	Contribute	ARRM	Y

SKG ID	Description	Rationale	Contribute or Close?		Additional Requirements?
II-C-2	Geotechnical properties of small body surface materials	Forces required to remove boulder, and response of surface, will depend on geotechnical properties. Analysis of forces required by spacecraft and pre- and post-removal images of surface will address.	Contribute	ARRM	N
III-A-1	Expected particulate environment due to impact ejecta	If dust detectors and/or appropriate imagers are implemented, the environment either at the target or at the returned boulder could be monitored	Contribute	ARM	Y
III-C-1	Small bodies as shields against solar storms.	If the appropriate sensors and mission operations are implemented, ARRM could contribute to this SKG during the cruise and DRO phase of its mission (hiding behind the boulder).	Contribute	ARRM	Y
III-C-1	Small bodies as shields against solar storms.	Could be examined experimentally on returned boulder.	Contribute	ARCM	Y
III-D-1	Local structural stability based on remote measurements.	ARM will contribute to this SKG during its detailed mapping and boulder manipulation phases.	Contribute	ARRM	N
III-D-2	Global structural stability based on remote measurements (mechanical strength of small bodies' sub-surface interior materials)	With the appropriate sensors, the process of detaching a partially buried boulder from the surface should contribute to understanding the mechanical strength of the asteroid subsurface.	Contribute	ARRM	Y
IV-A-1	Remotely identifying resource-rich NEOs (water content)	If spectrometers are used during the ARRM detailed mapping phase, this could provide a detailed map of OH/H2O on the surface of the asteroid.	Contribute	ARRM	Y
IV-A-1	Remotely identifying resource-rich NEOs (water content)	Science investigations of water content could be executed on the boulder during cruise.	Contribute	ARRM	Y
IV-A-1	Remotely identifying resource-rich NEOs (water content)	Science investigations of water content could be executed on the boulder by the crew.	Contribute	ARCM	Y
IV-A-1	Remotely identifying resource-rich NEOs (water content)	Subsequent Earth-based laboratory analysis of target samples to determine recoverable water content.	Contribute	ARM	Y

SKG ID	Description	Rationale	Contribute or Close?		Additional Requirements?
IV-A-2	Knowledge of how to excavate/collect NEO material to be processed.	Coring the boulder on the asteroid before collection.	Contribute	ARRM	Y
IV-A-2	Knowledge of how to excavate/collect NEO material to be processed.	Astronauts will collect samples from returned boulder, providing some insight into mechanical properties of NEO material.	Contribute	ARCM	N

III. Decadal Survey objectives addressed by ARM

The relevant chapter of the Decadal Survey is Chapter 4, “The Primitive Bodies: Building Blocks of the Solar System.” This contains two “Science Goals,” each with several “Specific Objectives.” Under each of the Specific Objectives, several “Important Questions” are listed.

The SAT identified 15 Important Questions from the Decadal Survey (tied to six Specific Objectives) that could be addressed by ARM with enhanced instrumentation and/or analysis. Two Important Questions were identified as being addressed by the ARM baseline mission (both tied to the same Specific Objective). As in the case of SKGs, most of the science contributions only occur if specific investigations are completed. In particular, many of them require either detailed spectroscopy of the target asteroid or laboratory analysis of samples returned to Earth. In addition, investigations involving organic material will only be possible if the target asteroid is rich in organic material (consistent with proposed target 2008 EV5, given what is currently known), and if the mission includes the kind of contamination knowledge and/or contamination control for returned samples discussed in the FAST report, measures that would not otherwise be required.

The two investigations that will address Decadal Survey objectives within the baseline configuration of ARM are both related to the objective to “determine the effects and timing of secondary processes on the evolution of primitive bodies.” The imaging system and lidar can contribute to the understanding of how the impact history of the target asteroid compares to that of comets and other asteroids, as well as to the understanding of how physical secondary processes such as spin-up result from non-gravitational forces.

A more detailed description of the Decadal Survey objectives that ARM may be able to address (including the relevance of an additional suite of instruments and measurements, and the constraints on the target asteroid) is given in Table 2.

Table 2. Decadal Survey Objectives that can be addressed by ARM

Science Goals	Specific Objectives	Important Questions	Rationale	ARRM, ARCM, or ARM?	Contingent on additional payload/additional human activity/post-mission analysis
Decipher the record in primitive bodies of epochs and processes not obtainable elsewhere	Understand presolar processes recorded in the materials of primitive bodies	How do the presolar solids found in chondrites relate to astronomical observations of solids disposed around young stars?	Subsequent Earth-based laboratory analysis of target samples may identify presolar solids.	ARM	Yes; Requires return of samples
		How abundant are presolar silicates and oxides?			
	Study condensation, accretion, and other formative processes in the solar nebula	How much time elapsed between the formation of the various chondrite components, and what do those differences mean?	Subsequent Earth-based laboratory analysis of target samples may identify primitive solids having condensed in different temperature regimes, information from isotopic studies.	ARM	Yes; Requires return of samples
		Did evaporation and condensation of solids from hot gas occur only in localized areas of the nebula, or was that process widespread?			
		Which classes of meteorites come from which classes of asteroids, and how diverse were the components from which asteroids were assembled?	Spectroscopic mapping of target object to potentially determine diversity of components from which the target is assembled and determine taxonomic types; high-resolution spectra of the asteroid surface to determine whether boulder is representative.	ARRM	Yes; Requires spectroscopy

Science Goals	Specific Objectives	Important Questions	Rationale		Additional Requirements?
Decipher the record in primitive bodies of epochs and processes not obtainable elsewhere (Continued)	Determine the effects and timing of secondary processes on the evolution of primitive bodies	How well can we read the nebular record in extraterrestrial samples through the haze of secondary processes?	Subsequent Earth-based laboratory analysis of target samples to determine thermal and aqueous alteration processes.	ARM	Yes; Requires return of samples
		How do the impact histories of asteroids compare to those of comets and KBOs?	Imaging system and lidar used to characterize shape, craters, boulders, and surface may contribute to the understanding of the impact history of the target asteroid.	ARRM	No
		How do physical secondary processes such as spin-up result from non-gravitational forces, the creation and destruction of binary objects, and space weathering?	Imaging system and lidar used to determine detailed shape model of target asteroid and distribution of regolith/boulders may contribute to understanding its history with regard to spin-up from non-gravitational forces.	ARRM	No
			Spectroscopic/color mapping of target asteroid may contribute to understanding the motion of regolith, which would relate to spin-up from non-gravitational forces.	ARRM	Yes
			Spectroscopic mapping of target asteroid may contribute to understanding space weathering.	ARRM	Yes; Requires spectroscopy
	Assess the nature and chronology of planetesimal differentiation	Did asteroid differentiation involve near-complete melting to form magma oceans, or modest partial melting?	Subsequent Earth-based laboratory analysis of target samples to assess heating of materials in early solar system.	ARM	Yes; Requires return of samples, differentiated asteroid target

Science Goals	Specific Objectives	Important Questions	Rationale		Additional Requirements?
Understand the role of primitive bodies as building blocks for planets and life	Determine the composition, origin, and primordial distribution of volatiles and organic matter in the solar system	What are the chemical routes leading to complex organic molecules in regions of star and planet formation?	Subsequent Earth-based laboratory analysis of target samples to determine composition and potential origin of volatiles and organic matter in target object.	ARM	Yes; Requires return of samples, organic-rich target
		What was the proportion of surviving presolar organic matter in the solar nebula, relative to the organic compounds produced locally?	Subsequent Earth-based laboratory analysis of target samples to determine if there is surviving presolar organic matter in target object.	ARM	Yes; Requires return of samples, organic-rich target
		What roles did secondary processes and mineral interactions play in the formation of organic molecules?	Subsequent Earth-based laboratory analysis of target samples to determine thermal and aqueous alteration processes.	ARM	Yes; Requires return of samples, organic-rich target
		How stable are organic molecules in different space environments?	Subsequent Earth-based laboratory analysis of target samples from different depths within boulder to determine depth dependence of degradation	ARM	Yes; Requires return of core samples, organic-rich target
	Understand how and when planetesimals were assembled to form planets	Are there systematic chemical or isotopic gradients in the solar system, and if so, what do they reveal about accretion?	Subsequent Earth-based laboratory analysis of target samples to determine chemical and isotopic composition of constituent components.	ARM	Yes; Requires return of samples

Science Goals	Specific Objectives	Important Questions	Rationale		Additional Requirements?
Understand the role of primitive bodies as building blocks for planets and life (Continued)	Understand how and when planetesimals were assembled to form planets (Continued)	How did Earth get its water and other volatiles? What role did icy objects play in the accretion of various planets?	Subsequent Earth-based laboratory analysis of target samples to determine composition and potential origin of volatiles and organic matter in target object along with isotopic studies of constituent components.	ARM	Yes; Requires return of samples

Appendix 1: List of acronyms:

ARM: Asteroid Redirect Mission

ARCM: Asteroid Redirect Crewed Mission

ARRM: Asteroid Redirect Robotic Mission

EVA: ExtraVehicular Activity

FAST: Formulation Assessment and Support Team

SAT: Special Action Team

SBAG: Small Bodies Assessment Group

SKG: Strategic Knowledge Gap

Table A.1. NEO/Phobos/Deimos Strategic Knowledge Gaps

	SKG Theme		SKG Categories		Specific SKGs
I	Human mission target Identification	A	Constraints on targets	I-A-1	Round trip limitations due to radiation exposure
				I-A-2	Reachable objects within planned architecture
		B	NEO orbit distribution	I-B-1	Long-synodic period NEOs having multiple mission opportunities
				I-B-2	Number of available targets at a given time
		C	NEO composition/physical characteristics (population/specific targets)	I-C-1	NEO sizes
				I-C-2	NEO albedos
				I-C-3	NEO rotation state
II	Understand how to work on or interact with small body surfaces	A	Biohazards and mitigation	II-A-1	Biological effects of small body surface particles
		B	Hazards to equipment and mitigation	II-B-1	Mechanical/electrical effects of small body surface particles
		C	Small body surface mechanical properties	II-C-1	Macro-porosity of small body interior
				II-C-2	Geotechnical properties of small body surface materials
		D	Mobility around and interaction with surface in microgravity conditions	II-D-1	Anchoring for tethered activities
				II-D-2	Non-contact close proximity operations for detailed surface exploration and surveys
		E	Habitat expansion options	II-E-1	Expanding habitat volume to small body interior for shielding and human factors
III	Understand the small body environment and its potential risk/benefit to crew, systems, and operational assets.	A	The particulate environment in the proximity of small bodies	III-A-1	Expected particulate environment due to impact ejecta
				III-A-2	Possible dust/gas emission via sublimation from volatile-rich objects
				III-A-3	The population of a particulate torus around the Phobos/Deimos orbits from micrometeoroid impacts and material ejected from Mars

	SKG Theme		SKG Categories		Specific SKGs
III	Understand the small body environment and its potential risk/benefit to crew, systems, and operational assets (continued)	A	The particulate environment in the proximity of small bodies (continued)	III-A-4	Possible particulate environment in the asteroid exosphere due to charged particle levitation following surface disturbances
		B	The ionizing radiation environment at small body surfaces, including contributions from secondary charged particles and neutrons produced in the regolith	III-B-1	Local effects on plasma and electrostatic environment from solar flare activity
				III-B-2	Small body surfaces as a source of radiation
		C	Mitigation strategies to preserve human health	III-C-1	Small bodies as shield against solar storms
		D	Local and global stability of small bodies	III-D-1	Local structural stability based on remote measurements
				III-D-2	Global structural stability based on remote measurements
IV	Understand small body resource potential	A	NEO resources	IV-A-1	Remotely identifying resource-rich NEOs
				IV-A-2	Knowledge of how to excavate/collect NEO material to be processed
				IV-A-3	Knowledge of extracting and collecting resources in micro-g
				IV-A-4	Prepositioning and caching extracted resources
				IV-A-5	Refining, storing, and using H & O in micro-g
		B	Phobos/Deimos resources	IV-B-1	Phobos-Deimos subsurface resource potential
				IV-B-2	Knowledge of how to access resource material at depth
				IV-B-3	Refining, storing, and using H & O in a usable state on Phobos-Deimos

Table A.2. Decadal Survey Specific Objectives

Science Goal	Specific Objectives
Decipher the record in primitive bodies of epochs and processes not obtainable elsewhere	Understand presolar processes recorded in the materials of primitive bodies
	Study condensation, accretion, and other formative processes in the solar nebula
	Determine the effects and timing of secondary processes on the evolution of primitive bodies
	Assess the nature and chronology of planetesimal differentiation
Understand the role of primitive bodies as building blocks for planets and life	Determine the composition, origin, and primordial distribution of volatiles and organic matter in the solar system
	Understand how and when planetesimals were assembled to form planets
	Constrain the dynamical evolution of planets by their effects on the distribution of primitive bodies