The Scientific Rationale for Robotic Exploration of Phobos and Deimos

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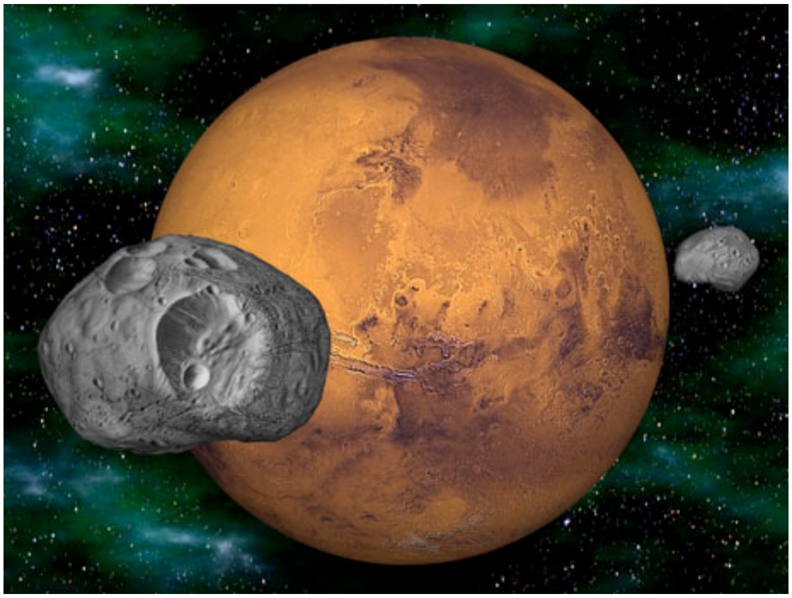


Executive Summary

Mars' two moons, Phobos and Deimos, have albedos, spectral properties, and densities indicating that they are members of the D class of small bodies. At the same time, the moons exhibit spectral evidence for distinct compositions suggesting distinct provenances, and their surface morphologies are dominated by the effects of different processes. Their presence in Mars orbit suggests that they are captured asteroids or extinct comets, and the most likely scenario places their time of capture during Mars' earliest history. As such, they may be the surviving representatives of a family of bodies that originated in the outer asteroid belt or further, and reached the inner solar system to deliver volatiles and organics to the accreting terrestrial planets.

The investigation of Phobos and Deimos cross-cuts disciplines of planetary science including the nature of primitive asteroids, formation of the terrestrial planets, and exobiology. Key science questions are the two moons' compositions, origins, and relationship to other solar system materials; what they reveal about delivery of volatiles and organics to the early inner solar system; and the geologic processes that affect primitive, D-type bodies. These questions can be investigated by a Discovery-class mission that includes measurements of bulk properties and internal structure, high-resolution imaging of surface morphology and spectral properties, and measurements of elemental and mineral composition. Phobos and Deimos are the only D-type bodies for which such a mission can be planned with extensive *a priori* knowledge of surface characteristics, reducing implementation risk. Because the two moons are potential staging areas and sources of resources for future human exploration of the Mars system, such a mission would contribute to human exploration in a way unique among small body missions.

An Overview of Phobos and Deimos

Nearly forty years since the first spacecraft encounters, the compositions and origins of the two moons of Mars remain obscure. They are difficult to observe from Earth, and much of our knowledge comes from brief observations of opportunity from spacecraft focused on Mars. The first spectral measurements of the moons, from Mariner 9 and Viking, revealed the moons' low albedos and an apparently gray color; the mass from radio science and volume from imaging indicated a density <2 g/cc. Based on these findings the moons were grouped spectrally with C-type asteroids, and interpreted to have a carbonaceous chondritic composition (Pang et al., 1973). This interpretation led to the hypothesis that Mars' two moons are captured primitive asteroids. The concept of the satellites as water-rich, carbonaceous objects led to proposals for utilization

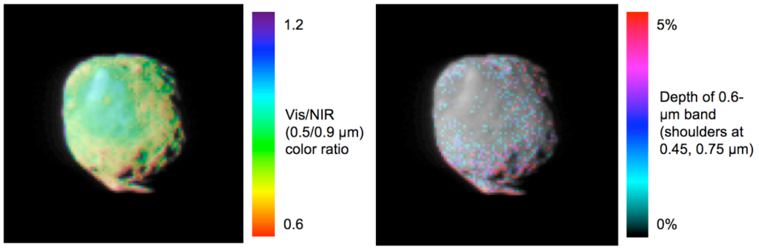
Fig. 1. Phobos (left) and Deimos (right) as viewed by the HiRISE imager on MRO. The large crater at left on Phobos is Stickney, exposing the bluer unit from depth in the moon

of their presumed resources in the human exploration of Mars, and consideration of them as bases or staging areas for exploration of the Martian surface.

New measurements and analyses over the last 20 years (e.g., Figs. 1 and 2) have provided an updated understanding of the moons. Phobos and Deimos are not C-type bodies as thought in the 1970's, but rather D-type bodies typical of the outer main asteroid belt, Trojan asteroids, and cometary nuclei. The original published spectra were a compilation from several sources. Subsequent, more accurate spectral measurements from ground-based telescopes (Grundy and Fink, 1991; Rivkin et al., 2002), HST (Cantor et al., 1999), and the Phobos 2 (Murchie and Erard, 1996), Mars Pathfinder (Murchie et al., 1999) and MRO (Murchie et al., 2008) spacecraft have found the Martian satellites to have a much higher visible-near IR spectral slope than C-type asteroids or most carbonaceous chondrites, placing them in the D class. Like most D-types, both moons also lack absorptions due to bound water that are present in many C-type asteroids (Rivkin et al., 2002). Phobos' density is 1.87 ± 0.06 g cm^{-3} and Deimos' is 1.54 ± 0.23 g cm^{-3} (masses from Konopliv et al., 2006), comparable to C- and D-type asteroids (Britt, 2002)..

There are at least two materials present on the moons' surfaces. Phobos 2 and MRO/HiRISE and CRISM images show that Phobos has a redder, background unit and a bluer unit associated with ejecta from Stickney crater (Avanesov et al., 1991; Murchie et al., 1991; Murchie and Erard, 1996; Murchie et al., 2008). MRO/CRISM has spatially resolved both of these materials as well as Deimos (Fig. 2). The redder unit appears primitive in composition, exhibiting an absorption feature at 0.65 μm due to Fe-bearing clays (Murchie et al., 2008) as is present in the most primitive carbonaceous chondrites (Vilas and Gaffey, 1989). In contrast the bluer unit is spectrally featureless. The redder unit cannot be related to the bluer unit by space weathering processes that weaken mineralogic absorptions, so it is inconsistent with "matured" Stickney ejecta. Further, Phobos' redder unit matches Deimos spectrally (Murchie et al., 2008). These results suggest that, at depth, Phobos has one composition, and that its shallow layer and Deimos are made of a distinct material; the two moons may have distinct compositions and origins.

It is well known from Viking images that the two moons are also distinct in their morphologic properties. Phobos is heavily cratered and dominated by the 9-km crater Stickney, located in the leading hemisphere. The crater is located near the center of symmetry of a system of a subradially arrayed grooves (Fig. 1) (Veverka and Duxbury, 1977; Veverka and Burns, 1980; Thomas, 1979). The grooves have been proposed to originate from drainage of regolith into fractures (Thomas, 1979), from exposed internal layering in a collisional shard (Horvath et al.,



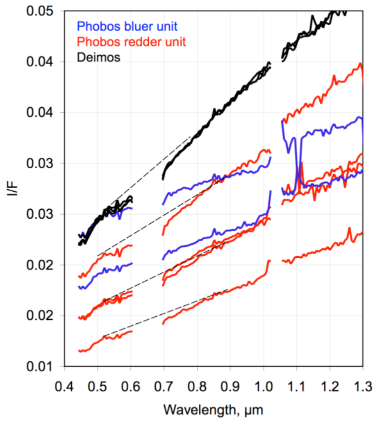


Fig. 2. MRO/CRISM measurements of Phobos and Deimos. Above is Phobos measured from a perspective similar to HiRISE's in Fig. 1, showing visible-IR spectral slope (left) and strength of the 0.65-µm band (center). Note the correlation of the band with redder spectral slopes. The plot at right shows the similarity of Deimos with Phobos' redder unit, including slope of the continuum and presence of a 0.65-µm absorption.

2001), or as chains of secondary craters from Stickney (Head, 1986). The grooves' orientations and morphology have also been modeled as the result of secondary impacts from ejecta of Martian basins (Murray et al., 2006). The rims and walls of the least degraded craters are elevated in albedo by up to 30%, consistent with exposures of material less altered by space weathering (Thomas, 1979).

In contrast, the surface of Deimos is extremely smooth at tens to hundreds of meters scales, and the moon's shape is faceted with highly rounded edges (Fig. 1). Albedo variations are dominated by bright streamers that originate at gravitationally high edges of facets, and trend down local slopes; darker material has accumulated at the gravitationally low centers of the facets (Veverka and Burns, 1980; Thomas, 1979). The streamers suggest that Deimos' surface morphology is shaped by slope and mass wasting processes in a thick regolith, whereas in contrast Phobos' surface morphology is shaped by impacts and effects of impact gardening (Thomas et al., 1996). Deimos' southern hemisphere is dominated by a hemispheric-scale concavity interpreted by Thomas et al. as a near-catastrophic crater, whose ejecta reaccreted as a massive, ~200 m-thick regolith layer (Thomas et al., 1996) and created the moon's smooth surface and rounded shape.

The dynamical environment and heliocentric distance of Phobos and Deimos result in an interesting regolith environment. Nearly all impact ejecta that escape either moon remains in Mars orbit, and reaccrete after ~10^4 yrs (Soter, 1971; Hamilton, 1996). Solar forces perturb the smallest ejecta particles out of the moons' orbits, such that ejecta from one moon can reaccrete onto the other (Krivov and Hamilton, 1997). Compared to regolith on primitive bodies in solar orbit, the regoliths of Phobos and Deimos are expected to have experienced greater effects from sterilizing radiation and space weathering processes (Clark et al., 1999). Finally, diurnal temperature variations are large, ranging from 340°K at local noon to as low as 100°K at night. The depth of the thermal wave is thought to be only about 1 cm, below which temperatures remain near 230°K (Kuhrt and Giese, 1989; Lynch et al., 2007)

Possible Origins

The low albedos and red spectral slopes of the moons of Mars are consistent with several different compositions, each having different implications for the moons' origins. The closest match in the asteroid population is found among outer asteroid belt and Trojan asteroids, D-type objects interpreted as rich in organic compounds and possibly having ice-rich interiors. Such objects are thought to be ultraprimitive, and to have experienced very little processing over solar system history. A relevant compositional analog is the Tagish Lake meteorite, an anomalous "ultracarbonaceous" chrondrite that may be more primitive than CI1 meteorites (Brown et al., 2000; Hiroi et al., 2001). The 0.65-μm band on Deimos and in Phobos' redder unit is consistent with the Fe-bearing phyllosilicates in these primitive materials (Vilas and Gaffey, 1989; Murchie et al., 2008). Such materials would not have condensed from the solar nebula at Mars' distance from the Sun, and they imply an origin as captured asteroids or extinct comets. Dynamically, this is difficult to accomplish late in Mars' history (Burns, 1992), but could have occurred as either moon passed through the extended atmosphere of Mars late during the planet's accretion (Hunten, 1979). Recent dynamical studies of the early solar system (the “Nice Model,” Gomes et al., 2005) suggest that D-type bodies may have been injected from the outer into the inner regions of the solar system (Morbidelli et al. 2005), although the this model has not been evaluated relative to the origin of Phobos and Deimos. If Phobos and Deimos are captured ultracarbonaceous bodies, they are among the scientifically richest small-body targets for robotic exploration. They would be ultraprimitive D-type bodies, and the two survivors of the family of bodies that actually delivered volatiles and organic to the accreting inner solar system planets, setting the starting conditions for the origin of life.

Other compositions and origins remain possible. Phobos and Deimos may consist of less primitive, CM-like carbonaceous material. Laboratory simulations of space weathering of these materials show that a red spectral slope characteristic of the moons can be induced by micrometeorite impacts (Moroz et al., 2004). In fact one anomalous CM-like carbonaceous chondrite, Kaidun, contains fragments of mutually incompatible lithologies including enstatite chondrites and differentiated igneous rocks, suggesting that it originated from a carbonaceous body trapped in orbit around a major planet, e.g. Mars (Ivanov et al., 1996, 2003).

The dark, red spectra of Phobos and Deimos approximate the theoretical end-member of an extremely space-weathered mafic composition (Lucey et al., 1995, 1998, 1999). Plausibly, either moon may be a shard or rubble from a satellite that co-accreted with Mars from material of ordinary chrondritic composition, masked by extreme space weathering. Alternatively, either may contain material ejected from Mars by large impacts (Britt and Pieters, 1988); this conjecture has not been evaluated quantitatively in light of recent findings that Mars' northern plains probably formed as a 11,000x9,000 km impact basin (Andrews-Hanna et al., 2008).

Although a primitive composition for either moon could provide an *in situ* source of hydrogen for future human exploration of Mars, the volatile content of the moons is unknown. There are no clear spectroscopic detections of water or hydroxyl, though Phobos 2/ISM data hint at bound water in some crater walls (Gendrin et al., 2005). Nor have organics been seen on the surfaces of the satellites, although the relatively high surface temperatures would lead to thermal crossover effects masking their strong absorptions near 3.4 μm.

Science Questions

There are four main motivations for robotic exploration of Phobos and Deimos:

- They are relatively accessible samples of D-type bodies, possibly with an ultraprimitive composition and surface features that reveal geologic processes on such bodies.
- The moons may have been captured late during Mars' accretion, with their bluer and redder materials sampling the diversity of materials that delivered volatiles and organics to the inner solar system.
- Understanding the origin of Mars' moons will provide insight into planetary dynamics that operated during the early solar system
- They may provide *in situ* resources and staging areas for human exploration of Mars.

The driving questions for robotic exploration of Phobos and Deimos derive from these motivations and from the science background outlined above. They include 6 science questions, given below in rough priority order, plus 2 exploration questions:

1. What are the compositions and origins of Phobos and Deimos?
2. What do they reveal about the early history and sources of volatiles of terrestrial planets?
3. What are the moons' internal structures? Does Phobos consist mostly of the material forming the bluer unit, shallowly covered by redder material?
4. What is the relationship of Mars' moons to each other?

5. What regolith processes occur on carbonaceous small bodies, and how do they compare with those on the more-studied S-types like Eros and Itokawa?
6. How did the grooves form on Phobos?

- What are the moons' hydrogen inventories and do they provide *in situ* resources?
- What are the mechanical and engineering properties of the moons' surfaces?

Phobos and Deimos have the only well-characterized surfaces among D-type bodies, and their location in high Mars orbit presents fewer mission and spacecraft design challenges than does exploration of D-types in the outer main-belt or among the Trojans. A mission to Phobos or Deimos would have less science or implementation risk than a mission to another D-type body.

Prospective Next Steps

Possible future robotic exploration of Phobos and Deimos falls into three tiers: opportunistic spacecraft encounters, a Discovery-class mission, and a New Frontiers-class mission. Given that Phobos and Deimos are distinct and different bodies, probably no one mission can answer all of the questions outlined above. If one assumes that the Russian Phobos-GRUNT mission will successfully characterize that moon and return a sample, a logical focus in the short term is the complementary exploration of Deimos.

Option 1: Opportunistic Spacecraft Encounters. Ongoing and future Mars orbital missions can obtain information that will reduce uncertainties in the moons' properties, but not answer any of the driving questions. Such data can be obtained from chance close encounters during high orbits, or as distant encounters from low orbit. The most important data would be spectral measurements that resolve brighter, fresher crater rims or albedo streamers, and close encounters of Deimos that include radio tracking and imaging to provide a better density estimate. No currently approved mission has capabilities to improve upon existing knowledge.

Option 2: A Discovery-class Mission. At least three alternate implementations could partially or fully address the majority of the driving questions outlined above. (a) A basic implementation would be a NEAR- to MESSENGER-like orbital mission with high-resolution imaging to map spectral units and morphology, X-ray and/or γ-ray spectroscopy to measure elemental abundances, and radio science and possibly lidar investigations to determine mass, shape, and density, and sounding of internal structure. (b) Constraints on composition would be improved by adding landed investigations to measure major and minor elements using an APXS or XRF, mineralogy using XRD, Mossbauer or Raman techniques, and soil mechanical properties. (c) Alternatively, the focus of the mission could be composition and origin, trading in capabilities for global characterization (e.g., lidar, sounding, X-ray and γ-ray spectroscopy) for enhanced compositional information. The Aladdin mission concept (Pieters et al., 2000) took this approach, using a "blast and grab" technique to collect and return to Earth sub-milligram samples of each moon.

Option 3: A New Frontiers-class Sample-return Mission. The NOSSE report classifies the collection and return of a sample of a near-Earth small body as a New Frontiers-class mission. By analogy, a mission to collect and return to Earth a large sample of Phobos or Deimos would fall into the same category. It would provide superior information on the history of the Mars system, if it included a robust imaging and gravity investigation of its target moon.

Relative Merits and Recommendation

Phobos and Deimos are representatives of D-type asteroids, that probably sample the diversity of materials that delivered volatiles and organics to the accreting terrestrial planets. Opportunitistic spacecraft encounters would only incrementally advance knowledge of them. Significant advances would come from a Discovery-class mission, which would prepare for eventual human exploration of the Mars system. Enhanced information on the moons' origin and evolution would follow from high-quality compositional measurements *in situ* or on a small (~milligram) regolith sample returned to Earth. We therefore recommend Phobos or Deimos as a high priority target for a near-term Discovery-class mission. A follow-up New Frontiers-class mission mission that returned a much larger sample could be warranted if the precursor mission found Phobos and Deimos to be ultraprimitive but not represented among known meteorites, and if human exploration and sample collection at Mars' moons was not in the forseeable future.

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