Science exploration architecture for Phobos and Deimos: The role of Phobos and Deimos in the future exploration of Mars

Ariel N. Deutsch a,*, James W. Head a, Kenneth R. Ramsley b, Carle M. Pieters a, Ross W.K. Potter a, Ashley M. Palumbo a, Michael S. Bramble a, James P. Cassanelli a, Erica R. Jawin a, Lauren M. Joziak a, Hannah H. Kaplan a, Connor F. Lynch a, Alyssa C. Pascuzzo a, Le Qiao a,c, David K. Weiss a

a Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02912, USA
b School of Engineering, Brown University, Providence, RI 02912, USA
c Planetary Science Institute, China University of Geosciences, Wuhan, Hubei 430074, China

Received 4 February 2017; received in revised form 4 December 2017; accepted 12 December 2017
Available online 18 December 2017

Abstract

Phobos and Deimos are the only natural satellites of the terrestrial planets, other than our Moon. Despite decades of revolutionary Mars exploration and plans to send humans to the surface of Mars in the 2030’s, there are many strategic knowledge gaps regarding the moons of Mars, specifically regarding the origin and evolution of these bodies. Addressing those knowledge gaps is itself important, while it can also be seen that Phobos and Deimos are positioned to support martian surface operations as a staging point for future human exploration. Here, we present a science exploration architecture that seeks to address the role of Phobos and Deimos in the future exploration of Mars. Phobos and Deimos are potentially valuable destinations, providing a wealth of science return, as well as telecommunications capabilities, resource utilization, radiation protection, transportation and operations infrastructure, and may have an influence on the path of the martian exploration program. A human mission to the moons of Mars would maintain programmatic focus and public support, while serving as a catalyst for a successful human mission to the surface of Mars.

© 2017 COSPAR. Published by Elsevier Ltd. All rights reserved.

Keywords: Phobos; Deimos; Mars; Human exploration; Mission architecture

1. Introduction

As NASA plans to send humans to Mars in the 2030’s (https://www.nasa.gov/content/nasas-journey-to-mars; e.g., Head et al., 2015), it is vital to gain a further understanding of the role of the martian moons, Phobos and Deimos, in this next stage of planetary exploration. These bodies may facilitate later exploration of Mars, through exploitation of in situ resources, by providing radiation protection, or through contributions to the continuity of the martian program. It is crucial that a mission architecture is developed to serve as a roadmap for the exploration of Mars’ moons focusing on the questions: “What is the origin of Phobos and Deimos?” and “What is the role of Phobos and Deimos in the future exploration of Mars?”.

Besides our Moon, Phobos and Deimos are the only known natural satellites of the terrestrial planets. We seek to understand why our Moon is different than the martian moons, and what their presence tells us about the moonless Mercury and Venus. Understanding these satellites can help us understand the origin and evolution of the
To date, the origins of Phobos and Deimos are still unknown. The hypothesized formation theories have specific and distinct implications for the possibilities of finding pristine martian crust, primitive material, or volatiles (e.g., Murchie et al., 2014). Depending on their composition, these moons could greatly facilitate Mars exploration (e.g., Oberst et al., 2014) (Table 1).

There are many strategic knowledge gaps concerning Phobos and Deimos science. Here we design a mission architecture that can, first, answer the fundamental scientific questions of the martian moons and, second, assess to what extent Phobos and Deimos can facilitate the later human exploration of Mars. This facilitation could occur in many ways (as discussed in-depth in Section 3), therefore it is crucial to develop a framework to serve as a roadmap before sending missions to Phobos and Deimos.

The major initial question driving our framework has a scientific motivation: “What is the origin of Phobos and Deimos?” The second question driving our framework asks how stopping at one or both moons could complement a human exploration program to Mars: “What is the role of Phobos and Deimos in the future exploration of Mars?”

To address the above questions, we outline major gaps remaining in Phobos and Deimos science that motivate future missions to the moons of Mars. We present a science exploration architecture consisting of orbiter, lander, and human exploration stages and discuss a framework designed to assess the role of Phobos and Deimos in the future exploration of Mars, specifically determining how these bodies might aid in the Mars program.

### 2. Strategic knowledge gaps in Phobos and Deimos science

Many unanswered questions regarding the formation and evolution of Phobos (Fig. 1) and Deimos exist today (e.g., Basilevsky et al., 2014; Murchie et al., 2014). Here we discuss the major gaps in the understanding of the origin and evolution of Phobos and Deimos that motivate the need for future exploration.

#### 2.1. Origin

Many formation hypotheses have been suggested for the origin of Phobos and Deimos. One hypothesis is that these moons are captured asteroid belt objects, consistent with compositional data and optical and spectral properties of Phobos and Deimos (e.g., Fraeman et al., 2012, 2014; Pajola et al., 2013; Pieters et al., 2014). Specifically, the low albedos, low densities, and spectral similarities of the moons to D-type asteroids are consistent with capture of outer solar system objects that are composed of primitive, carbonaceous material (Hartmann, 1990; Burns, 1992). Additionally, Phobos and Deimos have near-identical surfaces, so if they are captured, then they either are of the same original composition, or they are unrelated and have undergone extensive space weathering to produce near-identical surfaces (Murchie et al., 2014). The process of permanent capture, however, requires sufficient energy loss and has proven to be difficult to explain dynamically. Both Burns (1978) and Pollack et al. (1979) described qualitatively a possible method by which to capture a single object by aerodynamic drag in a circumplanetary envelope around Mars. Dynamical models that explore this phenomenon produce a Phobos spiraling toward Mars and a retreating Deimos (Hunten, 1979; Sasaki, 1990). While the physical properties of the moons suggest that they may be dark carbonaceous asteroids that were captured by Mars (e.g. Fraeman et al., 2012, 2014; Pajola et al., 2013; Pieters et al., 2014), the predicted orbital evolution due to the tides of the martian system suggests that the

![Fig. 1. Mars-facing side of Phobos, highlighting the linear grooves across the surface of the moon and Stickney crater in the left of the image. Image acquired by the High Resolution Stereo Camera from the Mars Express spacecraft on 22 August 2004. Pixel resolution of ~7 m. Image credit: ESA/DLR/FUB.](image)
moons originated on nearly circular, uninclined orbits not far from their current positions (Burns, 1992).

Alternatively, the moons of Mars, like other regular satellites, may be accretional products of orbiting debris in the planetary formation process (e.g., Burns, 1986). The small size of the bodies (Phobos is $27 \times 22 \times 18$ km (Archinal et al., 2011) and Deimos is $15 \times 12 \times 11$ km (Murchie et al., 2015)) may be explained by a bombardment of planetesimals sourced from the vicinity of Jupiter (Safronov et al., 1986). In this accretionary model, the moons are composed of material that is similar to that of Mars, and are enhanced in components that were brought in with the last heliocentric objects acquired by Mars (Burns, 1992). This model avoids the dynamical challenges associated with the capture model.

Finally, it is possible that the martian satellites are the result of a giant impact (Craddock, 2011; Citron et al., 2015; Rosenblatt et al., 2016). In this model, a planetesimal impacted Mars, resulting in the formation of an accretion disk around Mars. Material may have condensed and dissipated beyond the Roche limit, forming the satellites due to gravity instabilities within the disk. In this scenario, the moons are loosely aggregated material from the accretion disk and do not contain any volatile elements (Craddock, 2011; Citron et al., 2015; Rosenblatt et al., 2016).

Either of these major models offers the opportunity to explore interesting and important terrain, whether it be pieces of the outer solar system (e.g., Fraeman et al., 2012, 2014; Pajola et al., 2013; Pieters et al., 2014), building blocks of Mars (e.g., Burns, 1992; Rosenblatt and Charnoz, 2012; Peale and Canup, 2015), or material derived from a later giant impact with Mars, such as martian crustal or mantle composition (Craddock, 2011; Citron et al., 2015; Rosenblatt et al., 2016).

Different formation models imply different compositions for Phobos and Deimos (Table 1). If the bodies formed via co-accretion, then they are expected to have moderate water content of ~1 wt% (Saraian et al., 2014) and low carbon content (Murchie et al., 2014) with a composition similar to bulk Mars (Wanke and Dreibus, 1988). Similarly, products from a martian impact scenario are expected to have low water contents of $\leq 0.015$ wt% (Truong and Lee, 2017) and low carbon values (Murchie et al., 2014) with a composition of evolved martian crust or mantle, similar to SNC meteorites (McSween et al., 2009). In contrast, captured carbonaceous asteroids are expected to have relatively high (2–60 wt%) water contents (Murchie et al., 2014; Lee et al., 2017) and high carbon contents (Murchie et al., 2014). Thus, if the origin of the moons is determined to be capture, then the resource potential is strongest.

The volatile content, and by association the origin, of Phobos and Deimos are major knowledge gaps in planetary protection for future human missions. For example, Phobos and Deimos may contain materials that interacted with liquid water if they were derived from martian near-surface material (e.g., Lee and Lorber, 2015). Additionally, impacts can result in the transfer of materials from Mars to the moons (e.g., Ramsley and Head, 2013a). Therefore, both the mode of origin and material transfer processes have important implications for the planetary protection of Phobos and Deimos (Melosh et al., 2012).

The most critical knowledge gap that exists in Phobos and Deimos science is the origin of these moons. The only way to unequivocally resolve whether Phobos or Deimos are captured bodies, are native to the martian system, and differ in origin, is to send a scientific mission that will characterize the moons in unprecedented detail and return samples. Resolving the origin of the martian satellites is the top priority and may provide insight into the capture and evolution of asteroids or the formation and evolution of terrestrial planets.

2.2. Composition

The reflectance and spectral slope of Phobos and Deimos are similar to carbon-rich CI and CM carbonaceous chondrites (e.g., Hiroi et al., 2003). Although they share a similar spectral continuum slope to that of Mars crustal material, Phobos and Deimos have spectral reflectances that are a factor of two darker than even the most space-weathered Mars crustal material, suggesting this is not a good spectral analog (Pajola et al., 2013). Deimos is characterized by a spectrally homogeneous redder unit, while Phobos has two spectral units, a redder and a bluer unit.

Spectra acquired by the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) instrument onboard the Mars Reconnaissance Orbiter (MRO) reveal a broad, shallow absorption centered at $\sim 0.65$ $\mu$m on Deimos and on the redder unit on Phobos (Fraeman et al., 2014), which correlates with the visible color observed by both CRISM and the High Resolution Imaging Science Experiment (HiRISE) (Murchie et al., 2015). Both the bluer (although more weakly) and redder units on the satellites show a distinct absorption $\sim 2.8$ $\mu$m due to OH (Clark et al., 1990). These absorptions, the reflectance, and the spectral slope characteristics are consistent with a composition that is rich in phyllosilicate and that has been desiccated of H$_2$O (Murchie et al., 2015). Phyllosilicate-rich CM carbonaceous chondrites exhibit absorption features at $\sim 2.8$ $\mu$m attributable to OH and at $\sim 0.7$ $\mu$m due to Fe in phyllosilicate (Cloutis et al., 2011; Takir et al., 2013). Because the Fe feature observable in spectra of Phobos and Deimos is centered near $\sim 0.65$ $\mu$m, it has been suggested that Fe-bearing nontronite, a hydrous clay, is responsible and that the moons contain primitive material (Fraeman et al., 2014). Spectral mapping has also been done using thermal infrared spectra. Glootch et al. (2015) found evidence for bound water and carbonate on the surface of Phobos, consistent with the mineralogy of D-type asteroids observed in the Thermal Emission Spectrometer (TES) spectra. Alternative models of the origins of the moons involve anhydrous minerals. For example, space-weathering processes...
produce microphase and nanophase Fe (e.g., Pieters et al., 2000), and Rayleigh scattering from these particles may then cause curvature in the spectra near 0.65μm (Clark et al., 2012).

Determining the composition of the moons will place a primary constraint on the origin of these bodies. High-resolution spectral measurements and multiple targets of sample return are of top priority in characterizing the mineralogy and volatile content of the satellites, and should guide future scientific exploration of Phobos and Deimos.

2.3. Geology

Both Phobos and Deimos are characterized by low densities and low albedos, and have spectra consistent with those of primitive outer solar system bodies (e.g., Bell et al., 1993). Both bodies also have albedo streaks on the inner and outer slopes of crater rims suggesting large-scale downslope movement. On Phobos, these streaks are interpreted as talus and mass wasting mobilized in the geologically recent past (Basilevsky et al., 2014; Shi et al., 2016). Furthermore, thick (hundreds of m to km-size) mounds on the slopes and floors of craters are observed, and are interpreted as landslide deposits (Basilevsky et al., 2014). Despite the micro-gravity at the surface (surface gravity on Phobos and Deimos is 0.0057 m/s² and 0.003 m/s², respectively), impact-induced seismic shaking and surface movement produced by diurnal temperature changes can cause material to migrate along-slope (Basilevsky et al., 2014). Modeling of the formation of the albedo markings on Deimos suggests that vertical mixing, weathering, and creep, are important processes in the motion of material downslope, while impact gardening contributes very little (Thomas et al., 1996). A robotic mission to the surface is critical to measure the efficiency and frequency of material transport for the assessment of instrument and crew safety for surface operations on the moons.

Interestingly, despite these similarities, the regolith of Deimos may be unique because its surface shows conspicuous albedo patterns and is distinctively smooth (Thomas et al., 1996; Thomas et al., 2011). Understanding the relationship between Phobos and Deimos is another key question remaining today, which can partly be elucidated by determining the origin of each moon. For example, if the moons co-accreted with Mars, then they are compositionally related, however if the moons are captured bodies, then they may be unrelated or be fragments of a single parent body that was disrupted during capture (Singer, 2007; Rosenblatt, 2011). Additionally, because the moons may have been in closer orbits originally, regolith exchange between the two bodies may have occurred via a hypothesized dust belt (Soter, 1971) and thus sample returns of both moons are required to test whether the redder unit of Phobos could be derived from Deimos (Murchie et al., 2015). Understanding such differences is essential to characterizing the formation and evolution of small bodies in the solar system.

2.3.1. Grooves on Phobos

Parallel grooves exist on the surface of Phobos (Fig. 1) and are typically ~100 to 200 m wide and several km long, defined by chains of coalescing pits of nearly the same diameter, grooves with scalloped margins, and grooves with roughly linear margins (e.g., Thomas et al., 1979; Basilevsky et al., 2014; Murray and Heggie, 2014). Several families of features are defined by intersecting systems that have approximately the same orientation (Thomas et al., 1979). Grooves are continuous features; often observed cutting through large craters and rims with no gaps, and even intersecting other families of grooves without displaying lateral offset at intersections (Basilevsky et al., 2014).

Many formation models exist to explain the origin of these unique features. One possible explanation is that the grooves formed as fractures or faults due to tidal forces (e.g., Soter and Harris, 1977; Weidenschilling, 1979; Dobrovolskis, 1982; Hurford et al., 2016) or drag forces upon capture (Pollack and Burns, 1977; Thomas et al., 1979). This explanation is consistent with the linear morphology of the grooves and the cross-cutting relationships with relatively older craters (Basilevsky et al., 2014). Bruck Syal et al. (2016), however, modeled that the resulting damage patterns to Phobos from the Stickney-forming impact are unrelated to the grooved terrain.

Alternatively, it is possible that these grooves were formed as chains of secondary impacts from Mars ejecta (e.g., Murray et al., 1992, 2014; Murray and Illiffe, 2011). In this model, each family of grooves represents a single impact event on Mars. The zone of avoidance on the trailing hemisphere of Phobos is explained by the velocity of Phobos’ forward motion exceeding the ejecta velocity. However, Ramsley and Head (2013b) plotted precise Keplerian orbits for Mars ejecta to test this hypothesis and found that this hypothesis is not consistent with Mars ejecta emplacement models and observations. Specifically, they found that to emplace the observed grooves, grid patterns of (often tens of thousands of) ejecta fragments must be produced with nearly identical diameters, launched with virtually zero rates of dispersion into fixed patterns of arrays, which is statistically unlikely to occur. Additionally, they calculated that the volume of Mars ejecta that has intersected Phobos is at least three orders of magnitude less than what is required to produce the grooves (Ramsley and Head, 2013a,b, 2014). Furthermore, such groove-forming impacts would produce ~25 to 50 m of new regolith on Phobos, burying features that are clearly observable today, such as spectral units and boulders (Ramsley and Head, 2014). Other small bodies in the solar system have similar groove-like features, but lack a nearby body for crater-forming material to originate (Basilevsky et al., 2014).

Similarly, other researchers have suggested that the grooves formed as chains of secondary impact craters or
ejecta from Stickney (e.g., Veverka and Duxbury, 1977; Head and Cintala, 1979; Davis et al., 1980).

Finally, it is possible that the grooves are the remnant tracks of rolling and bouncing boulders (Head and Wilson, 2011; Bruck Syal et al., 2016). Ejecta clasts may have slid, rolled, and bounced at distances comparable to the observed groove lengths, crushing the regolith and pushing it aside as they moved (Head and Wilson, 2011). There are weaknesses to this model, namely that (1) there is a distinct lack of boulders found at groove terminations and (2) there is a lack of gaps where grooves cross positive topography, which are expected to occur after a boulder crosses a positive landform and bounces (Basilevsky et al., 2014). However, degradation of boulders since the formation of the grooves may have destroyed the blocks (Basilevsky et al., 2014). Also, the velocities of blocks ejected during the formation of Phobos’ Stickney crater permit the formation of continuous grooves across crater interiors and rims (Wilson and Head, 2015).

In summary, none of the proposed formation mechanisms can suitably explain all features of the grooves. Important remaining strategic knowledge gaps (SKGs) are whether the origin and nature of the grooves on Phobos, and on other small bodies, are of the same genesis. Furthermore, what prevents Deimos from having these linear features? A mission to Phobos can elucidate these enigmatic features by specifically testing these proposed mechanisms.

Different groove evolution scenarios may influence traversibility constraints on Phobos for both robotic and human exploration. For example, a highly fractured surface may introduce stability constraints, and if groove formation is still active today, then this creates an active safety hazard. Secondary impacts create chains of craterers with difficult slopes to navigate. Finally, remnant tracks may have rogue boulder and ejecta clasts in the terrain creating navigational obstacles. Overall, each model presents its own set of navigational obstacles as explorational assets approach a set of grooves, but none preclude exploration.

2.4. Age

Another fundamental question regarding the moons of Mars is the age of the bodies. Stickney crater (Fig. 1) is the largest crater on Phobos (~9 km in diameter). Schmedemann et al. (2014) derived crater production and chronology functions for two end-member scenarios of the dynamical evolution of Phobos: Case A assumes that Phobos has been in its current orbit around Mars since its formation and Case B assumes a recent capture with an impact history of a typical Main Belt Asteroid. The authors suggest that (1) Phobos formed or experienced a major collision at 4.3 Ga (Case A) or 3.5 Ga (Case B), (2) Stickney crater formed at ~4.2 Ga (Case A) or 2.6 Ga (Case B), and (3) the grooves formed at ~3.1 to 3.8 Ga (Case A) or 44–340 Ma (Case B) (Schmedemann et al., 2014). More recent work, however, suggests that many craters on the surface of Phobos are the result of a secondary impact spike produced from the Stickney-forming impact ejecta, and that the surface age of Phobos may not be derived accurately by counting such craters (Ramsley and Head, 2015, 2017). An alternative age for Stickney crater of <0.5 Ga was derived by Ramsley and Head (2015, 2017) using the evidence of boulders and ejecta blocks from Stickney (Thomas et al., 2000), boulder destruction rates (Basilevsky et al., 2013, 2015), and space weathering rates of Phobos regolith (Pieters et al., 2014). An essential objective of a Phobos mission should be resolving the age paradox of Stickney crater, given that age estimates for this feature span ~3 Ga. Consequentially, placing absolute ages on different features and materials on the surface of Phobos or Deimos will provide insight into the age, formation, and origin of these bodies.

3. Exploration architecture

We developed a framework of scientific questions to assess prior to sending humans to the moons of Mars. In order to determine the role of Phobos and/or Deimos in the future exploration of Mars, their near-surface physical and chemical characteristics must be understood. To gain an understanding of these properties, the key question that initially drives this framework is: What is the origin of Phobos and Deimos? Several formation models have been proposed, as discussed in Section 2.1. Each formation model has distinct implications for the utility of Phobos and Deimos in the human exploration of Mars (Table 1), where a captured body would provide the most resources.

The SKGs can be broadly divided into three categories: (1) the composition, (2) overall surface characteristics, and (3) geophysical properties of Phobos and Deimos (Table 2). Compositional characterization will include orbital-scale mapping of compositional units in the VIS, IR, and near-IR, sample return of redder and bluer spectral units, and identification and distribution of potential resources. Surface geologic characterization will include global high-resolution imaging and topographic characterization. Finally, geophysical characterization will include defining physical properties of regolith, global mapping of the near-surface gravity field, and mapping the internal structure of both bodies.

For human exploration of the moons, answers to SKG categories 1 and 2 (Table 2) feed forward into in situ resource utilization (ISRU) capabilities. The composition and geological characteristics have critical implications for sample return sites and ISRU targeting. If Phobos is a spectrally bluer body that is covered by a redder mantle due to space weathering or dust, then one sampling site is sufficient to acquire samples from both units (Basilevsky et al., 2014). If Phobos is heterogeneous, however, then multiple sampling sites are required to understand the history and composition of the moon (Basilevsky et al., 2014). Furthermore, the spatial scale and distribution of these units must be well characterized before any sample
acquisition instrumentation is deployed, which is a major goal in the orbital phase of our exploration framework (Fig. 2, Stage I).

SKG categories 2 and 3 (Table 2) feed forward into traversing capabilities. Understanding the geological and geophysical properties has specific implications for detailed traversibility maps for future robotic and human missions. Details of surface geology, specifically regolith properties (e.g., dielectric constant and porosity), surface structure, compactness, slope measurements, and landslide hazards, are critical for the characterization of environmental hazards.

We have devised a two-mission-architecture (Fig. 2) to address our science-driven questions with the added benefit of providing key information for later missions involving human exploration.

3.1. Robotic exploration of Phobos and Deimos

The main science goal of this mission is to characterize the surface of Phobos and Deimos using both orbital spacecraft instruments and a smaller landed spacecraft, and to provide returned samples for confirmation of the in situ compositional analysis, similar to the objectives of the attempted Russian sample return mission Fobos-Grunt (Marov et al., 2004). Our architecture is patterned off of the Hayabusa 2 mission (Tsuda et al., 2013) in both spacecraft infrastructure and mission operations, and involves an initial orbital mapping stage, detachment of the landed assets and operation throughout their lifetime, and is followed by spacecraft sample acquisition and sample return to Earth. The robotic mission is composed of two stages (Fig. 2, Stages I–II).

3.1.1. Stage I: orbital exploration of Phobos and Deimos

The orbital phase of the robotic exploration architecture (Fig. 2, Stage I) is designed to address the major SKG: the origin of the moons. As discussed in Section 2.1, there are many origin hypotheses that have been proposed to explain the moons of Mars, and each has distinct implications for the composition and utility of the moons (Table 1). The orbiter includes a laser altimeter, high-resolution camera, spectrometer, and gravity ranging system. The tangible science products of the orbital mission include global topographic coverage of Phobos and Deimos generated by orbital stereo imaging and laser altimetry, global imaging of Phobos and Deimos at sub-meter resolution, global compositional mapping of Phobos and Deimos via orbital spectroscopy, and a global map of the near-surface gravity field.

The products of Stage I are designed to address SKG categories 1 and 2: the compositional and surface characterization of Phobos and Deimos (Table 2). There are many feed-forward benefits of this mission. First, we will produce detailed maps for future mission planning for both robotic and human exploration, which are essential when assessing the safety of the terrain, but also when selecting the most scientifically interesting sites for surface exploration. Composition maps will play a crucial role in traverse planning for sample collection and resource targeting. Second, a compositional understanding of surface materials and properties provides information on traversibility and sample collection priorities. Third, we analyze the potential resource availability and distribution. High-resolution spectrometers that provide diagnostic elemental abundances and mineralogy of fresh, non-space-weathered surfaces are critical in resolving the abundances of major and minor elements and the compositions of specific units. This provides vital evidence required to constrain the origin of the moons. Furthermore, high-resolution topographic measurements and color observations of the grooves on Phobos can test different groove formation models, because each model makes different predictions for the topography of groove rims and floors and

Table 2
SKGs for Phobos and Deimos exploration.

<table>
<thead>
<tr>
<th>Category 1: Composition</th>
<th>What is the origin of each body?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>What factors contribute to the low density of Phobos (i.e. water ice or pore space)?</td>
</tr>
<tr>
<td></td>
<td>How thick is the regolith?</td>
</tr>
<tr>
<td></td>
<td>What makes up the distinctive blue and red units on Phobos?</td>
</tr>
<tr>
<td></td>
<td>What is the mineralogy and petrology of Phobos and Deimos?</td>
</tr>
<tr>
<td></td>
<td>What is the quantitative abundance of Mars ejecta in regolith?</td>
</tr>
<tr>
<td></td>
<td>What is the quantitative abundance of H$_2$O- and OH-bearing phases?</td>
</tr>
<tr>
<td></td>
<td>What is the quantitative abundance of organic, C-bearing phases?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Category 2: Surface characteristics</th>
<th>What are the regolith mechanical properties?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>What is the age of Stickney crater and how does it relate to the crater size-frequency distribution?</td>
</tr>
<tr>
<td></td>
<td>What are the origin, distribution, and age of the boulders on Phobos?</td>
</tr>
<tr>
<td></td>
<td>What is the origin of the grooves on Phobos?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Category 3: Geophysical properties</th>
<th>What is the internal structure of Phobos and Deimos?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>What factors contribute to the low density of Phobos?</td>
</tr>
<tr>
<td></td>
<td>What is the radiation dose at each body?</td>
</tr>
<tr>
<td></td>
<td>What is the global shape and rotational state of each body?</td>
</tr>
<tr>
<td></td>
<td>What is the gravitational field at each body?</td>
</tr>
</tbody>
</table>

...
the stratigraphic relationships between groove floors and rim materials (Murchie et al., 2015). In addition, determining the density to find the internal macroporosity and volume of the bodies is important in constraining the deep structure of the moons and possible deep water-ice inventory (Murchie et al., 2015).

3.1.2. Stage II: landed exploration of Phobos/Deimos

The objective of Stage II is to characterize the structure of Phobos, and to provide an enhanced sample suite for the compositional diversity of Phobos by utilizing a robotic lander that will also have roving capabilities (Fig. 2, Stage II).

The landed mission is designed to characterize the surface at higher spatial resolution to prepare for future robotic and human surface operations. The landed instrumentation has mobility, assembled onto “hedgehog robots,” which are specifically designed to operate in low-gravity conditions and rough surfaces (Pavone et al., 2013). These cube-shaped robots can hop and tumble on the surface, independent of one another, while also safely housing instruments (Pavone et al., 2013). The landed}

---

**Fig. 2. Flowchart illustrating the scientific exploration framework for Phobos/Deimos. Orbital phases are highlighted in blue, landed phases are highlighted in green, and human exploration phases are highlighted in yellow. Red “no” boxes suggest that the answer to the specified question cannot be determined or that Phobos/Deimos do not offer a particular resource along the path in human martian exploration. The exploration to Mars via Phobos/Deimos is a weighted algorithm of many factors. Multiple “no’s” do not necessarily warrant a halt in the exploration framework. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)**
components allow for in situ hyperspectral imaging, visible imaging, measurements of the magnetic field, and acquisition of infrared and thermal data, from a wide range of locations. Finally, Stage II will also employ sample collection in order to quantitatively confirm spacecraft/lander observations and to produce samples for laboratory analysis on Earth, for the curation of samples for long-term storage and global community retrieval. Terrestrial laboratories will allow for the comprehensive analyses of the mineralogical, elemental, and isotopic composition of samples at a level of detail that is not possible with robotic rendezvous.

The lander payload is specifically designed to investigate the electrical, mechanical, and porosity properties of the regolith, characterize the internal structure of the body in order to quantify how competent the body is, and to return a substantial sample collection of several grams. These products seek primarily to address SKG categories 1 and 3: the compositional and geophysical characterization (Table 2). The data obtained from this stage, informed by the previous stage, should provide an answer to our driving science question of “What is the origin of Phobos and Deimos?” The specification and scope of subsequent landed missions depend on the results from the prior mission.

The feed-forward benefits of Stage II are related to assessing the safety of the martian moon system for human exploration and to appraising the value that the moons can offer in radiation/micrometeorite/dust protection, technology development, and resources. We will produce a detailed characterization of surface conditions including the radiation environment to determine the necessary radiation-protection shelter required for humans and instruments. The orbital debris environment must be characterized in order to assess possible hazards from regolith dust. We will gain experience working and roving in the micro-gravity environment in preparation for using real-time computer-assisted traverses to guide humans around the surface in later missions. Finally, the distribution and abundance of important resources for supporting human operations or providing sources for fuel, such as hydrated minerals and carbon, will be characterized at high resolution.

Note that in Fig. 2, beginning in Stage II, each of the questions terminate in the selection of either “yes,” to continue along the mission framework, or “no,” to end that route of inquiry. We do not suggest that a single “no” is enough to preclude Phobos or Deimos from aiding in the exploration of Mars, but rather that that particular question failed to provide a potential merit in doing so. Thus, multiple “no’s” should not necessarily prevent a human exploration program to the moons of Mars. The answer to this driving question is a weighted algorithm of each of the termini where the most important factor is determining to what extent Phobos/Deimos can aid in the future exploration of Mars. The flowchart also includes a cyclic option for additional, independent landed missions as needed to address the defined SKGs (Fig. 2, dashed lines).

3.2. Stage III: assess role of human exploration of Phobos/Deimos

The objective of Stage III (Fig. 2) is to determine whether humans can successfully and safely operate on the surface of the moons using Stage I–II science. Stage III is an exploratory phase that is not an additional mission, but in which we re-assess the results of the preceding robotic exploration of the moons (Stages I–II). Specifically, we seek to determine if the debris, radiation, gravity, and rotational environments are understood in sufficient detail to address astronaut safety concerns (Fig. 2, Stage III).

Before sending astronauts to the moons of Mars, we must understand the influence of micro-gravity on astronaut health. Long-duration spaceflight to the martian system and a basecamp in a micro-gravity environment such as Phobos or Deimos present several health risks due to the hostile space environment, including loss of bone mass, muscle atrophy, cardiac dysrhythmias, and altered orientation (Blaber et al., 2010).

These three topics (the debris, radiation, and gravitational environment) are essential in characterizing the environment for human safety. The following two topics, gravitational and rotational states, are imperative for operational success.

Characterizing the debris environment (Fig. 2, Stage III) is critical in identifying any potential hazards in the near-surface environment for both human explorers and infrastructure. Ejecta from impacts into Mars typically impacts the surface of Phobos with a velocity of 2–3 km/s, producing ejecta from secondary impacts on Phobos with velocities <800 m/s, and subsequently 95–99% of the Phobos ejecta remains in orbit around Mars (Ramsley and Head, 2013a). In contrast, ejecta that is produced by primary impacts on Phobos has higher velocities, and a smaller proportion of material re-impacts or is gravitationally captured (Ramsley and Head, 2015). Understanding the frequency of impacts as well as the dust and debris trapped in the orbital environment is an important aspect of assessing the safety of human operations on the moons.

In addition to dust, it is important to quantify the radiation environment and the effects of long-term exposure to both humans and instrumentation (Fig. 2, Stage III). The location of the base may help reduce radiation exposure. For example, surrounding terrain may help provide protection, such as if the surface operation base is settled within Stickney crater on Phobos. In this configuration, nearly one hemisphere of radiation is blocked by Mars and Phobos (Mueller and Metzger, 2015). In addition, a regolith of sufficient thickness (~2 to 5 m) may provide an adequate radiation shielding effect to stop secondary radiation, caused by cosmic radiation shattering nuclei in the target material (Mueller and Metzger, 2015). In this case, it may
be useful to coat the habitat in regolith material. Alternatively, water may provide yet the best shielding material.

The gravitational and rotational states of the body are critical to quantify and map before arrival for the operational design of instrumentation, equipment deployment, and traversibility maps (Fig. 2, Stage III). Small bodies characteristically have non-intuitive vectors for surface acceleration, derived from irregular shapes, rapid spin, low mass, and tidal effects (Murchie et al., 2015). These factors can create a particularly challenging environment for humans to navigate, thus pre-calculated traverses based on the potential energies over the surface are necessary for operational success. Although the micro-gravity environment will present operational challenges to the crew, it also contributes to exploration by promoting more gentle-walled craters compared to lunar highland craters of the same size (Basilevsky et al., 2014). Shallower slopes provide safer terrains for building camp and for robotic and human traversing. If these fields are well characterized and conditions are safe for human explorers, proceed to the final framework phase, Stage IV.

It is possible that planned upcoming missions (Table 3) can fulfill Stages I–III of the framework by characterizing the origin and thus the distinct utility of the moons, as well as the safety and operational constraints of the martian system. These missions (Table 3) have similar payloads to the origin and thus the distinct utility of the moons, as well as the safety and operational constraints of the martian system. These missions (Table 3) have similar payloads to what we have suggested in Section 3. With the tentative dates planned for sample returns to Earth in the late 2020’s (Table 3), it is possible that the framework permits human missions to the moons in the 2030’s.

3.3. Stage IV: human exploration of Phobos/Deimos

The final stage of the mission framework consists of a suite of tasks that human explorers can accomplish on the moons of Mars (Fig. 2, Stage IV). Early design reference scenarios were constructed for manned missions to Phobos and Deimos by O’Leary (1985) and Aaron (1988), and continue to be developed by the Mars Moons Team at Johnson Space Center (Gernhardt, 2015, 2016). These design concepts suggest that humans could accomplish substantial science at Phobos while establishing early leadership in the martian system and continuing programmatic exploration (O’Leary, 1985; Aaron, 1988; Gernhardt, 2015, 2016).

We first and foremost note that humans can accomplish science (Fig. 2, Stage IV). Humans can greatly increase the efficiency in sample collection and sample return capacity by drilling for and collecting deep geologic samples (Crawford, 2012). Humans can also make observations of other targets, including Mars and the neighboring moon. They can also sample large ejecta blocks, and identify and sample exogenic materials (Lee et al., 2017). The scientific output achieved by humans is substantial and human explorers can greatly assist in resolving remaining SKGs, and additional SKGs that develop as the mission exploration framework proceeds and new data are collected.

In addition, humans can set-up and operate an ISRU extraction base (Fig. 2, Stage IV) to harness regolith and silicate minerals (which host, e.g., silicon, iron, aluminum) for building materials, carbon for fuel, or possible hydrated minerals for water or propellant (Nichols, 1993). Additionally, sunlight can be harnessed as a source of solar energy. A variety of derive resources can be produced from available materials including plastics made from carbon and metals and ceramics refined from silicate minerals, and carbonaceous materials can be processed for carbon, hydrogen, and nitrogen in refueling and life support operations (O’Leary, 1985). If the moons are determined to be of a captured origin, then we expect these materials to be much more abundant (Table 1), and thus the moons offer more resource potential in aiding martian operations.

Humans can also increase the potential for large-scale exploratory activities by deploying large-scale and complex equipment and can further the development of a space-based infrastructure by providing routine and emergency maintenance of the complex equipment and habitat (Crawford, 2012). Finally, an important manufacturing task for human crews may include the creation of heat shields and extraction of metals to 3D-print spare parts (Mueller and Metzger, 2015).

Furthermore, humans can demonstrate the capability to operate in a micro-gravity environment, which has not yet been experienced by humans (Fig. 2, Stage IV). Humans

<table>
<thead>
<tr>
<th>Mission</th>
<th>Agency</th>
<th>Objectives</th>
<th>Timeline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mars Moon eXploration&lt;sup&gt;a&lt;/sup&gt;</td>
<td>JAXA</td>
<td>– Determine origin of moons&lt;br&gt;– Understand processes in circum-martian environment</td>
<td>Launch 2024&lt;br&gt;Mars arrival 2025&lt;br&gt;Earth arrival 2029</td>
</tr>
<tr>
<td>Phobos sample return&lt;sup&gt;b&lt;/sup&gt;</td>
<td>ESA-ROSCOSMOS</td>
<td>– Study bulk characteristics of martian moons&lt;br&gt;– Return surface samples from Phobos&lt;br&gt;– Demonstrate and mature technologies required for Mars sample return missions</td>
<td>Launch 2024&lt;br&gt;Mars arrival 2025&lt;br&gt;Earth arrival 2027</td>
</tr>
</tbody>
</table>

<sup>a</sup> Fujimoto et al. (2017).
<sup>b</sup> Chalex et al. (2014).
can assist in the incremental development of technologies tested in the martian system as they are challenged by a new environment.

On the surface of Phobos or Deimos, humans can also build and maintain a telecommunications base (Fig. 2, Stage IV). Early Mars missions may not land on Mars due to the high financial cost of, and need for, improved Entry, Descent, and Landing (EDL) technologies. A human mission to Phobos can assist with the emplacement of a simple Mars telecommunications network, either with a series of satellites providing low-Mars-orbit transmission and reception relay capabilities on different orbits, or by the emplacement of aerostationary satellite capabilities. Alternatively, astronauts on Phobos can oversee robots on the martian surface in preparation for later human landings on Mars. These robotic operations may include mining activities, creating propellants for Mars ascent, and building landing pads – all productive steps forward in NASA’s evolvable Mars campaign. We suggest that this will not only be significant in the preparation for human arrival on Mars, but also critically important in the continuation of the martian program.

Finally, humans may construct radiation protection from surface regolith with ISRU equipment (Fig. 2, Stage IV). This is a vital task that can help lower the radiation dose for both human crewmembers and electronics, as discussed in Section 3.2.

4. Discussion

Both Phobos and Deimos are interesting exploration destinations that warrant further exploration on their own merit. The scientific exploration architecture discussed here is designed to explore both bodies robotically in orbital and lander phases (Stages I–II). When considering human exploration, however, we also consider factors of human safety and infrastructure safety and reliability.

One major constraint for human exploration of the martian moons is that both bodies have low escape velocities; the escape velocity of Phobos is 11.39 m/s while that on Deimos is only 5.56 m/s (Gernhardt, 2015, 2016). Such an extreme micro-gravity environment presents a major challenge to field astronauts, who can potentially launch themselves off the body without expelling substantial energy. For example, a suited crewmember who jumps vertically with a 2 m/s take-off velocity reaches a vertical height of 1.2 m on the Moon, and reaches back down to the surface in 2.5 s (Gernhardt, 2015, 2016). On Phobos, however, this same suited crewmember would reach 350.9 m above the body, and not return to the surface for 11.7 min (Gernhardt, 2015, 2016). And on Deimos, the trip would last for 22.2 min as the crewmember peaked at 666.7 m (Gernhardt, 2015, 2016).

Another issue for human exploration is extended exposure to radiation. Stickney crater on Phobos, however, has the potential to provide additional radiation shielding for instruments and crews. Setting up a base within the crater can potentially block nearly one hemisphere of radiation (Mueller and Metzger, 2015), which could amount to a substantial reduction in radiation dose over time.

While both Phobos and Deimos warrant further scientific exploration, we conclude that Phobos is the most viable human exploration target because of its higher surface gravity, greater escape velocity, and more potential radiation shielding. However, the scientific exploration framework presented here (Fig. 2) is designed to explore both targets robotically in order to address the scientifically driven SKGs (Table 2) defined for the moons of Mars. Both moons are explored to determine the nature and origin of these enigmatic bodies. During the human exploration phase, observational periods of Deimos take place with high-resolution equipment to further characterize the fellow moon of Mars (Fig. 2, Stage IV).

Sending humans to the surface of Phobos presents several advantages over going directly to Mars. Overall, the bulk cost of sending humans to the surface of Phobos is considerably less than it is to send astronauts to the surface of Mars; Phobos can be reached much sooner than Mars, and for a far lower monetary and human risk cost. Through this exploration science framework, we have shown that the moons of Mars are exciting as both scientific and exploration destinations. The regolith of Phobos may offer the opportunity to study small bodies/asteroids, martian material, and volatiles on a single surface, while answering a variety of SKGs (Table 2). It has been proposed that samples that are collected robotically on Mars can be cached on the surface of Phobos for humans to retrieve later (Stooke, 2014; Lee et al., 2017).

As exploration targets, Phobos and Deimos offer stable orbital platforms for Mars observations and communications. Furthermore, the journey to these moons requires a minimal delta-V from the Earth, making them a favorable destination in comparison to the more challenging Mars (O’Leary, 1985). Finally, a successful human program to Phobos undoubtedly serves as a catalyst for getting humans to Mars.

If no humans are sent to Mars before we are prepared for a surface landing on the planet, then decades may elapse before we are prepared for the journey. Phobos, however, presents key programmatic advantages in sending humans to the martian system as intermediate steps to ensure continuity in the martian program: (1) Phobos is a technically achievable martian target, requiring only low-cost near-term development of lunar and/or ISS systems (Lee et al., 2005). (2) A journey to Phobos reduces risk for a Mars landed mission through a stepwise program and technology demonstrations (Lee et al., 2005). (3) Phobos exploration enables the achievements of an exciting and high-science return mission in the near term to the martian system, maintaining programmatic focus and continued public support (Lee et al., 2005).

Thus, Phobos and Deimos present strong cases to support the future exploration of Mars. Their roles in
supporting the future exploration of Mars are largely driven by: (1) the strong science return that visiting these small bodies guarantees, specifically in addressing their origin and composition (Table 2), and most importantly (2) a successful human program to Phobos is a catalyst for a successful human mission to Mars and ensures a steady cadence of meaningful, near-term missions in the martian system (Lee et al., 2005).

5. Conclusions

There are still many unknowns surrounding the nature and origin of the moons of Mars, and further robotic missions are required to characterize these bodies. These missions may also reveal to what extent Phobos and Deimos can enhance the martian exploration program. Here we have developed an architecture for what must be assessed before we can send humans to the surface of these moons. Programmatic logic may dictate sending humans to Phobos or Deimos, in which case this mission framework is critical when structuring a human precursor mission. We believe that sending humans will always be beneficial based on the scientific output they can accomplish.

Phobos and Deimos are positioned to support Mars surface operations. A Phobos mission establishes early leadership by sending humans to the martian system to explore, conduct resource surveys, and establish a scientific station that builds upon martian assets and can allow for sample return of both martian and Phobos regolith to Earth for detailed analysis (Aaron, 1988). If the moons contain hydrated minerals, mining may be a key strategy for affordable Mars campaigns. While both moons are interesting exploration destinations, we conclude that Phobos is a safer target due to higher surface gravity, greater escape velocity, and more potential radiation shielding. Furthermore, Phobos may provide a suitable location for astronauts to maintain a telecommunications network. ISRU operations may include the production of heat shields and 3D-printing spare parts. The exploration of Phobos is potentially an affordable and productive first-step toward surface operations on Mars. Overall, Phobos is a scientifically interesting destination that offers engineering, operational, and public engagement benefits that most importantly would allow for the continuation and development of the Mars exploration campaign in the upcoming decade.

The exploration framework laid out here seeks to address how Phobos and Deimos can aid in the future exploration of Mars. Phobos and Deimos are potentially valuable commodities, providing a wealth of science return, as well as telecommunications capabilities, resource utilization, radiation protection, transportation and operations infrastructure, and the continuity of the martian exploration program.

Acknowledgements

We gratefully acknowledge the NASA Solar System Exploration Research Virtual Institute (SSERVI) for sponsoring the graduate seminar “Phobos and Deimos: The Moons of Mars,” which motivated this work. We also thank Dr. John Grunsfeld, former Associate Administrator for the Science Mission Directorate and NASA Astronaut, and NASA Astronaut Mike Gernhardt for helpful discussions about this framework. We thank Ernesto Palomba and Peggy Ann Shea for editorial handling of the manuscript and two anonymous reviewers for insightful reviews.

References


