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The value of Phobos sample return

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ABSTRACT

Phobos occupies a unique position physically, scientifically, and programmatically on the road to exploration of the solar system. It is a low-gravity object moderately inside the gravity well of Mars. Scientifically, it is both an enigma and an opportunity: an enigma because the origins of both it and Deimos are uncertain, and provide insights into formation of the terrestrial planets; and an opportunity because Phobos may be a waypoint or staging point for future human exploration of the Mars system. Phobos is a low albedo, spectrally bland body with a red-sloped continuum. It appears similar to D-type objects more commonly found in the outer asteroid belt and Jovian space (Rivkin et al., 2002), but occurs in an orbit that is difficult to explain by capture (Burns, 1992). It might have a primitive composition like that inferred for outer solar system objects or it could be related to Mars and, for example, be composed of Martian basin ejecta. Regardless, Phobos has acted as a witness plate to Martian debris over the age of the solar system. The moons may possibly be a source of in situ resources that could support future human exploration in circum-Mars space or on the Martian surface. in situ compositional analyses can address many questions relevant to preparation for future human exploration. Sample return resolves those questions while also enabling detailed analyses in terrestrial laboratories to address higher order questions, many of which have not yet been asked.

1. Characterizing the composition of Phobos: science and exploration objectives

There are several goals to acquiring detailed compositional measurements of Phobos or Deimos: solving the question of the moons' origins, understanding geochemical processes on these two moons of Mars, understanding the early geologic history of the Mars environment, and preparing for future human exploration. In situ measurements address aspects of the first and last goals, and can make contributions to the second. However only detailed measurements of returned samples in a geologic context are fully sufficient to address all four goals.

1.1. *Solving the problem of the moons' origins*

There are two main classes of hypotheses to explain the origin of the Martian moons, capture or formation in situ (Table 1). Both are closely tied to compositional interpretations of their optical and spectral properties (e.g., Fraeman et al., 2012, 2014; Pieters et al., 2014). Capture of outer solar system objects composed of primitive, carbonaceous material (Hartmann, 1990; Burns, 1992) would explain Phobos' and Deimos' low densities, low albedos, and spectral similarity to D-type bodies in the outer asteroid belt and the Trojan asteroid population, by virtue of inherent properties of the constituent materials. In contrast, capture of inner solar system objects of presumed ordinary chondritic composition requires a high degree of space weathering to alter spectral properties of mafic silicate material to resemble the spectral properties of Phobos and Deimos. Space weathering occurs on the Moon and near-Earth asteroids through deposition of submicroscopic iron-rich rims on regolith grains from impact-generated vapor and solar wind sputtering (Pieters et al., 2000; Hapke, 2001), darkening and reddening the spectra of silicate minerals and masking their mineral absorptions. If Deimos and Phobos are captured, then they are either of the same original composition or have experienced extensive space weathering to produce near-identical surfaces. If the latter, the two bodies may be unrelated and may sample the diversity of materials delivered to the inner solar system during the early history of the terrestrial planets.

Dynamical models have been explored that allow the capture of Phobos and Deimos only through very specific conditions and by invoking aerodynamic drag by an early Mars protoatmosphere (Hunten, 1979; Sasaki, 1990). In this context, the orbits of Phobos and Deimos are difficult to explain because they are both near-circular and near-equatorial with synchronous rotational periods,

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Table 1
Compositions predicted by different models for the origin of Phobos.

Origin Hypothesis	Composition predicted	Elemental abundances	Mineral abundances
Capture of organic- and water-rich outer solar system body	Ultra-primitive composition; Tagish Lake is the best known analog (Brown et al., 2000)	High C; high Zn/Mn; high S; composition possibly unique from known meteorites	Abundant phyllosilicates; carbonates and organic phases; anhydrous silicate phases rare
Capture of organic- and water-poor outer solar system body	Anhydrous silicates plus elemental carbon (Emery and Brown, 2004)	High C; Mg/Fe ratio ~2–4; bulk composition unlike any meteorite analogs	Anhydrous, med. Fe (20–40%) pyroxene+olivine; abundant amorphous carbon or graphite?
Capture of inner solar system body	Composition like common meteorites (e.g. ordinary chondrites) (Brearley and Jones, 1998)	Mg/Si ~0.8–1, Al/Si ~0.05–0.1; Zn/Mn & Al/Mn ratios separate known meteorites; likely low C	Low carbonates, phyllosilicates; pyroxene, olivine probably in range of known meteorites
Co-accretion with Mars	Bulk Mars; similar to ordinary chondrites but specific SNC-derived comp. (Wanke and Dreibus, 1988)	Mg/Si, Al/Si, Fe/Si indicative of bulk Mars; low C; Zn/Mn, Al/Mn like ordinary chondrites	Anhydrous silicates with Fe, Mg of bulk Mars; low abundance of C-bearing phases
Giant impact on Mars	Evolved martian crust or mantle, like SNC meteorites, Mars rocks or soil (McSween et al., 2009)+impactor	High Al/Si, Ca/Si, lower Fe/Si, Mg/Si indicative of evolved igneous materials	Evolved, basaltic mineralogy consistent with many datasets for Mars

and Phobos spirals toward Mars whereas Deimos retreats. Burns (1992) thus favored formation in situ over capture.

In situ formation of the Martian moons avoids the dynamical challenges of capture. In situ formation by co-accretion with Mars (Safronov et al., 1986) predicts a composition similar to bulk Mars. If formed by co-accretion, then the moons offer the opportunity to explore directly the building blocks of Mars. In situ formation resulting from accretion of material derived from a giant impact on Mars (Craddock, 2011) predicts a Martian crustal or mantle composition, perhaps mixed with impactor material. If so, the moons offer the opportunity to explore the composition of Mars' crust and mantle as they existed early in the planet's history. In either case, extreme space weathering is required to mimic the spectral properties of Phobos and Deimos.

The most recent spectroscopic data for Phobos and Deimos come from the Observatoire pour la Mineralogie, l'Eau, les Glaces et l'Activité (OMEGA) onboard Mars Express (MEx) and the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) on Mars Reconnaissance Orbiter (MRO) (see Fraeman et al., 2012, 2014). These data reveal extremely subtle spectral features that mimic a primitive, carbonaceous composition, yet ambiguity in their interpretation illustrates the need for higher-quality compositional measurements. The moons' spectra exhibit no evidence for H_2O absorptions like those present in some primitive carbonaceous chondrites, though they do exhibit evidence for OH; desiccation may result from the space environment and relatively high daytime temperature (Lynch et al., 2007). Resolving Phobos' (or Deimos') composition, and thus its origin, requires additional information on its mineralogic, elemental, and isotopic composition that can be obtained in situ and from a returned sample.

Different models for Phobos' origin predict compositions analogous to different meteorite types (Table 1). Expected mineralogical and elemental abundances can be predicted from laboratory measurements of these meteorites. The differences between the major hypotheses could be significantly addressed using in situ techniques such as X-ray diffraction, Raman spectroscopy, or X-ray fluorescence (e.g., Murchie et al., 2012). Analysis of a returned sample in a terrestrial laboratory allows detailed elemental and isotopic analyses and provides the most unambiguous means to distinguish among the hypotheses.

1.2. Understanding the nature of small bodies orbiting Mars

If Phobos is a captured asteroid, then most of its mass may be low-albedo, primitive, carbonaceous material, perhaps a cousin to D-type bodies of the outer asteroid belt and could thus provide invaluable insights into solar system processes. An essential measurement is the hydration state of Phobos. D asteroids are, in general, thought to be volatile-bearing, but no unambiguous evidence of absorption features due to molecular water has been detected in spectra of Phobos (Murchie and Erard, 1996; Rivkin et al., 2002; Fraeman et al., 2012, 2014). It may be that Phobos' high daytime surface temperature and generation of an impact-fragmented, space-weathered regolith (Thomas, 1998) have desiccated hydrated minerals to several cm or greater depth. However D-type asteroids at greater solar distances typically also lack molecular water absorptions, leading to the possibility that their compositions are in fact anhydrous silicates (Emery and Brown, 2004). Either detailed in situ measurements that are sensitive to a broad range of minerals or returned sample could determine which possibility is correct.

A second insight could be into chemical evolution of the protoplanetary disk. Models predict heliocentric gradients in isotope ratios (e.g., D/H) and chemistry (e.g., Aikawa et al. 1996; Millar et al. 2003). Proposed mechanisms for the origin of isotope anomalies, in particular for oxygen and nitrogen (Clayton 2000; Young and Lyons 2003), rely on photochemical reactions that most likely vary with heliocentric distance. These predictions are testable by comparing existing meteorite data, representing the main asteroid belt, to data obtained from samples of primitive materials from further out in the solar system. Comparisons between oxygen ($^{18}O/^{16}O$, $^{17}O/^{16}O$), hydrogen (D/H), nitrogen ($^{15}N/^{14}N$), and carbon ($^{13}C/^{12}C$) isotope ratios obtained from meteorites and samples of Phobos would shed light on the relation of Phobos to Mars and bodies of the outer solar system as well as the applicability of disk chemistry models to the early solar system. Isotopic measurements of sufficient accuracy probably require analysis of returned samples.

Finally, if Phobos is a captured asteroid, it could provide a range of primitive organic material. Organics record low temperature chemistry that initiated in the interstellar medium, continued through the energetic phases of the birth of the solar system, and culminated on accreted planetesimals. If Phobos is primitive in composition, it provides an opportunity to link the chemical history recorded in the organic component of an asteroidal body with the wealth of data currently being obtained from studies of chondritic meteorites. To date, the vast majority of what is known about extraterrestrial organic matter is derived from chondritic meteorites (predominantly CI and CM carbonaceous). Within CM and CI meteorites carbonaceous material is present at levels of ~2–4 wt% and resides in the matrix, where the mineralogy reflects a history of both high water activity (e.g., abundant phyllosilicate) and oxidation (e.g., abundant magnetite). The most abundant organics could be characterized in situ using any of several techniques including Raman and mass spectroscopy. More detailed analysis of organics, especially at low abundances, would require returned samples in terrestrial laboratories.

1.3. A witness plate to the history of Mars

If Phobos accreted in place from a debris disk of Martian crust and mantle ejected by a giant impact in the early history of the solar system, for example that which formed the Borealis basin (Andrews-Hanna et al., 2008; Craddock, 2011), then nearly the entire moon would be composed of Martian materials that record the earliest Martian crustal formation. Currently, the primary resource for understanding Martian geochemical evolution are the >100 Martian meteorites (for simplicity called SNCs, after the initials of the first three identified meteorites, Shergotty, Nakhla, and Chassigny) that were ejected off of Mars by impact events over the past 20 million years. Although in-depth study of these meteorites has revolutionized our understanding of Martian geochemistry and geological history, SNCs nevertheless provide an extremely limited sampling of the Martian crust. There is only a single sample in the collection older than 2.1 billion years, ALH84001 (4.5 Ga), representing the sole example for the pre-Noachian through early Amazonian periods during which most of Mars' geologic units were emplaced (Fig. 1). This meteorite sampling bias may arise from impact fracturing and weathering of Noachian and Hesperian rocks that weakens them relative to young, unweathered Martian basalts common among the SNCs. The stresses of ejection and acceleration to escape velocity probably favor survival of recent basalts over fractured, weathered ancient crustal materials.

Isotopic systematics of basaltic Martian meteorites indicate that mantle differentiation and resultant geochemical characteristics of their source regions occurred early in Martian evolution, perhaps as early as $\sim$4.5 Ga (Borg et al., 1997). Most Martian meteorites are fractionated, obscuring crucial geochemical information on early Martian differentiation. If Phobos accreted from Martian ejecta, samples from it would provide a more complete view of early Mars, dominated by pre-Noachian rocks older than the oldest preserved Martian surface units. Surviving material would contain a unique record of Mars geology that will be difficult to obtain from SNC meteorites or from direct robotic sampling of the Martian surface because of fracturing, burial, and alteration of the oldest pre-Noachian crust. Whereas gross mineralogy could be determined in situ, detailed analysis of isotopic systematics requires a returned sample.

Whether Phobos accreted in place or was captured from outside the Mars system, it has nevertheless served as a witness plate

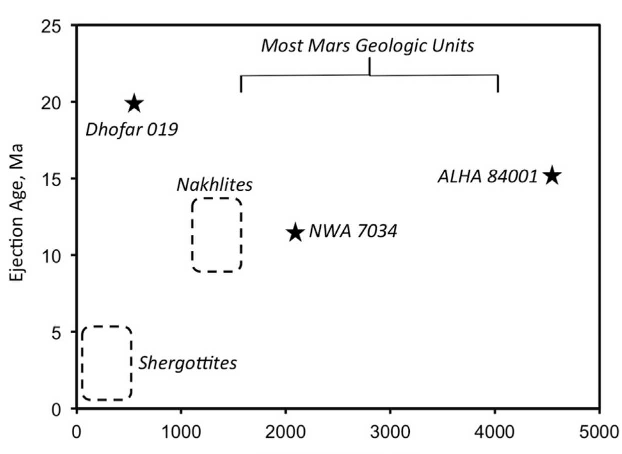

Fig. 1. Crystallization ages vs. ejection for the SNC collection. The time period during which most Martian geologic units formed is highly underrepresented.

that collected and retained material ejected from Martian impact events over geologic time. The existence of Martian meteorites is proof that materials from Mars are ejected by impacts with sufficient energy to escape Mars gravity and to reach Earth; they must also pass the orbit of Phobos (Bogard and Johnson 1983; Gladman 1997). Phobos will naturally have intercepted some of this material. Samples of Mars incorporated into Phobos' regolith are likely to be much more representative of the bulk crust than are SNC meteorites. The lack of information about the sample provenance is balanced by the diversity of rocks likely to have been sampled. Impact craters and basins occur globally on Mars. The bulk of the crust is significantly older than the SNCs, and the planetary differentiation process can best be understood by studying the petrology, geochemistry, and geochronology of these as yet unsampled rocks. The ultramafic composition of the only meteoritic sample of the ancient crust is almost certainly not representative of the whole crust. Additional samples will help us piece together how the planet differentiated, how the crust evolved from the mantle, and whether crustal evolution proceeded from homogeneous mantle reservoir or a complex series of isolated reservoirs.

Unfortunately, if Phobos does not originate from Martian material, then Martian material reaching Phobos as ejecta would be challenging to identify and interpret. Ramsley and Head (2013) have calculated that the fraction of Noachian and younger ejecta in Phobos regolith is of order hundredths of a percent. Moreover, that material has impacted Phobos at a relative velocity of 2–3 km/s, such that besides being low in concentration it must be highly fragmented and difficult to recover. Recovery of meaningful information from this trace component would almost certainly require analysis in terrestrial laboratories.

1.4. Preparing for future human exploration

Phobos is viewed as a potential staging area for future human exploration of Mars. Part of its attractiveness arose in the 1970s with the first interpretation that Phobos could be compositionally analogous to water-bearing carbonaceous chondrites, and thus a potential source of resources for future human explorers (Pang et al., 1978). Extracting consumable materials from the Mars system for life support or the return trip to Earth, known as In Situ Resource Utilization (ISRU), eliminates considerable mass that would have to be carried to Mars, making the spacecraft smaller (Drake, 2009). The consumables could include water for human consumption, hydrogen and oxygen extracted from the water for fuel, or carbon to combine with hydrogen to produce methane as fuel. Because of Phobos' proximity to the Martian surface it could also serve as a base to support telepresence and remote surface operations. Surface operations at Phobos could include retrieval of a Mars surface sample collected, cached, and launched to orbit robotically, tele-operation of rovers on Mars' surface, and exploration of Phobos itself.

At the present time, however, the extent of potential resources on Phobos is unknown, and the logistics of extracting them if they are there remain uncertain. There are four major subjects on which current knowledge is insufficient to ascertain Phobos' potential for resources and its value as a staging area, so-called "strategic knowledge gaps" (Carr et al., 2012). These are described in Table 2 and include: whether there is hydrogen in bound water or hydroxyl, and whether there is carbon; the nature of debris and radiation hazards in the immediate vicinity of Phobos; the logistics of space operations at Phobos' surface; and the engineering properties of the regolith from which resources would be extracted. First and foremost, there has never been a repeatable detection of water in Phobos' regolith, and the amount of OH is unknown and depends on whether it is surficial and formed from

Table 2
Gaps in knowledge required for human exploration of the Mars system can be closed by dedicated Phobos missions.

Strategic knowledge gap	Science/engineering objective	Measurement requirement
What is the potential for in situ resource utilization from Phobos for a human mission to the Mars system	Assess the potential for providing water and hydrogen and oxygen for fuel	Determine abundances and characteristics of H_2O, OH-bearing phases
	Inventory the carbon resources for fuel production	Measure abundances of organic, C-bearing phases
What are the hazards for future astronauts in Mars orbit?	Determine human tissue effects of the radiation environment	Measure radiation dose at different energy levels
	Constrain the Mars orbital debris environment	Measure particle density of dust belts while in elliptical orbit before Phobos proximity operations
What are the physical constraints on space operations near Phobos?	Determine global shape and rotational state	Measure global shape using stereo imaging or laser altimetry
	Determine the gravitational field with high fidelity	Measure mass and mass distribution using Doppler tracking during proximity operations
What are the engineering issues associated with obtaining resources from Phobos?	Determine regolith composition	Measure mineral and elemental abundances, particularly for hazardous phases
	Measure regolith mechanical properties	Determine geotechnical properties by imaging sample collection or with penetrometer

solar wind, or intrinsic to Phobos (Murchie and Erard, 1996; Rivkin et al., 2002; Fraeman et al., 2012, 2014). The negative results for H_2O suggest an upper limit of a few tenths of a percent weight-equivalent water at the optical surface. Possibly only the surface is anhydrous, due to desiccation during space weathering; chemically bound water could remain at depth. However, any water initially present as ice is predicted to have ablated over the age of the solar system to a depth of kilometers (Fanale and Salvail, 1989).

Second, if there are in situ resources on Phobos, environmental hazards encountered during their recovery are uncertain. High-energy particle radiation from the Sun and cosmic rays encountering Phobos' surface generate an unknown amount of secondary radiation. Perhaps more significantly, Phobos resides in an unusual environment where regolith particles ejected from both moons create a flux of reimpacting debris. Hamilton (1996) studied the orbital dynamics of micrometer- to millimeter-scale particles ejected from Phobos and Deimos and found that the particles are significantly perturbed by solar radiation effects and Mars' oblateness. Particles larger than about 30 μm can remain in Martian orbit for 2000–25,000 years before ultimately being reaccreted at meters to hundreds of meters per second velocity, forming “dust belts” surrounding the orbit of each moon.

Third, Phobos' shape and gravity are poorly known, compared to those of “traditional” targets for human exploration, the Moon and Mars. There is reasonable detail known about surface morphology, local slopes, crater density, and block distribution (Thomas and Veverka 1980). Mass is known to better than 1%, but shape is more poorly known to about 2% uncertainty in global volume (Jacobson, 2010).

Fourth, basic properties of the regolith are unknown. Key questions include what minerals are present, abundances of highly volatile elements such as carbon and sulfur, and geotechnical properties including whether the regolith is fluffy or compact, its particle size-frequency distribution, and its adhesive properties (such a tendency to coat spacesuits or equipment). Based on the most recent spectral interpretation that Phobos' closest bulk compositional analog could be CM carbonaceous chondrite (Fraeman et al., 2014), there is a remote possibility that some Phobos regolith materials could be hazardous. The CM meteorite class contains serpentine-family minerals (Cloutis et al., 2011) that in finely powdered form in regolith could adhere to an astronaut's suit, be brought into a crew habitat, and be inhaled.

Measurements taken during Phobos proximity and landed operations could close the gaps in strategic knowledge required for human exploration of Mars' moons. Return of samples could establish the availability of resources, and the mineral, elemental, and isotopic composition of the regolith. For initial assessment a variety of in situ measurements is thought to be sufficient (Carr et al., 2012), including measurements of major and minor elements and mineral phases. Images of the site of the measured or collected sample, and/or use of a penetrometer or a mechanical properties experiment, would help reveal the geotechnical properties of the regolith. A radiation experiment could characterize the secondary radiation environment. A dust particle counter on the spacecraft would place constraints on the particle density in the moons' “dust belts”. Finally, the shape and volume of Phobos could be determined much more accurately than now known during proximity operations using either of two techniques: laser ranging, like that used to measure the shape of asteroids Eros (Zuber et al., 2000) and Itokawa (Abe et al., 2006), or stereo photoclinometry, which was used to measure the shapes of Itokawa (Gaskell et al., 2006) and Vesta (Gaskell, 2012).

2. Advantages of sample return

Sample return has a range of advantages over remote sensing or in situ investigation of Phobos for determination of geochemical characteristics of Phobos' regolith. First, laboratory measurements of returned samples use state-of-the-art techniques unconstrained by equipment volume, mass, and power, all of which are constrained for spacecraft instrumentation. Laboratory instrumentation is part of a worldwide community of continuous improvement, evolution, and experimentation. In the years or even decades following a sample return mission, laboratory measurements of curated sample have often moved orders of magnitude ahead of what was previously achievable technically.

Second, laboratory results typically are far more accurate and precise that those from robotic instruments, using any extant or foreseeable technology. For example, Amelin (2000) achieved precisions of better than 1 million years (0.02%) for absolute Pb–Pb ages on 4.56 Ga inclusions from chondritic meteorites. In contrast, current precision estimates for in situ robotic radiogenic age measurements of Noachian Mars rocks are 3–4 orders of magnitude worse than for these laboratory measurements, typically ±10–20%. A ±10% error on a Martian ancient crustal sample would equate to a hundreds-of-million year error, making it impossible to resolve the events of Noachian period and the late heavy bombardment. Many of the major advances in planetary science were achieved by analyzing small amounts of sample (see below).

Third, returned samples can be analyzed under controlled conditions and prepared in a way optimized for a particular analysis. The selection and preparation of samples in terrestrial laboratories is extremely exacting, and in some cases impossible to replicate with robotic instrumentation. The routine functions of an experienced researcher in selecting and preparing samples for analysis would be challenging in terms of mass, power, and volume to replicate robotically. Another major factor speaks to the core of the scientific method. In terrestrial laboratories analyses can be repeated, replicated and verified by a variety of analytical methods; these protocols fundamental to the scientific method can be technically implausible or unaffordable for remote or in situ techniques.

A particular challenge to the design and precise functionality of remote and in situ spacecraft instrumentation is the combination of vibration, thermal variation, shock, radiation, dust, and outgassing characteristic of space environments. This range of factors is disruptive to accurate calibration and precision of in situ instruments. Maintaining accurate calibration in these environments is challenging, and one of the reasons why robotic instrumentation tends to be less precise than laboratory instrumentation used to analyze returned samples.

For low albedo bodies such as Phobos and Deimos, which have albedos in the range of 2–7%, admixture of opaque phases responsible for their low albedo highly complicates remote mineral identification. Laboratory studies of silicate phases typical of carbonaceous chondrite with similar albedos, for example phyllosilicates, show that just a few percent of opaques can obscure weaker, overtone and combination absorptions diagnostic of these phases (Clark, 1983). At opaque abundances of ≥20%, only the strongest fundamental absorptions remain distinct. Because Phobos and Deimos are such low-albedo bodies, the information obtainable from reflectance spectroscopy is limited. Confident identification of the mineralogy of dark objects requires other techniques, either in situ or in the laboratory using returned samples.

The legacy of returned samples continues to provide new insights as laboratory capabilities expand. One of the first things that Apollo 11 astronaut Neil Armstrong did on the lunar surface was to scoop a "contingency sample" of approximately 1 kg of lunar soil. From first analyses of that limited sample, the basic framework of early lunar differentiation and volcanism were discovered (Wood, 1970). Using *more modern techniques*, far more can be determined (e.g., Taylor et al., 2006). Zolensky et al. (2000) described a tiered analysis whereby the first microgram analyzed in a modern laboratory could reveal comparable knowledge about the geochemical reservoir from which the sample was drawn. That theoretical treatment proved true in practice when the regolith sample returned from asteroid Itokawa by the Hayabusa mission was unexpectedly small. The returned micrograms-sized sample settled the relationship between S asteroids and ordinary chondrites (Nakamura et al., 2011), and revealed processes distinct from those on the Moon whereby S asteroid regoliths are space weathered (Noguchi et al., 2011).

3. The sampling environment

Phobos has the advantage of being a relatively well-investigated small body of the inner solar system, providing tactical knowledge needed to plan a sample return mission. Because of its proximity to Mars, Phobos has been investigated from Mars orbiters using a variety of remote sensing technologies. Its surface morphology and spectral properties have both been mapped at the reconnaissance level.

For planetary protection purposes, a Phobos sample return would likely be a Class V mission with unrestricted Earth return. It is highly unlikely that returned sample could pose a risk of introducing active or dormant biological material to the Earth (Clark et al., 1999). In addition to the desiccating environment, Phobos is exposed to solar UV radiation on its surface to a depth of a few microns, to ionizing radiation from the Sun that penetrates a few centimeters, and to protons from galactic cosmic radiation that penetrate several meters. The part of Phobos that is easily accessible to a sample return mission, regolith within 30 cm of the surface, accumulates a radiation dose that reduces the viability of spores by 12 orders of magnitude in less than 500,000 years. A reduction of viability of a microorganism by 6 orders of magnitude is considered to be an effective level sterilization. Thus, the potential of returning a living entity from Phobos is extremely low. The best analog to exposure at the surface of Phobos is at the surface of the Moon.

4. Mission option examples

There has been one recent flight mission for a Mars moon sample return that failed shortly after launch, and three proposed missions involving remote sensing and in situ science or sample return that were evaluated to different levels, but ultimately not selected for flight. These are discussed below along with a mission concept for more detailed in situ analysis and sample return. This comparison highlights the tradeoff between science return, science focus, and expenditure of resources.

4.1. Phobos-GRUNT (Russian in situ and sample return mission)

Built by the Russian Space Agency and designed by NPO Lavochkin (Marov et al., 2004), Phobos-GRUNT was launched on November 9, 2011. This ambitious mission included a sample collection and return system, a landing system, a remote sensing package, and a survey satellite from the China National Space Administration. The mission plan called for the spacecraft to land on Phobos and use a robotic arm to collect and deliver up to 200 g of regolith to the sample return system, which would be launched from the landed spacecraft upon completion of the sampling phase. The return stage included a small capsule that would enter Earth's atmosphere and aerodynamically brake to 30 m/s with a no-parachute hard landing at the Sary Shagan test range in Kazakhstan. The landed stage, which included a gas-chromatograph package (thermal differential analyzer, gas-chromatograph, and mass-spectrometer), gamma ray spectrometer, neutron spectrometer, alpha particle X-ray spectrometer (APXS), seismometer, radar, visible/near-infrared spectrometer, dust counter, and ion spectrometer, would have remained on Phobos making in situ measurements for up to one additional year. The spacecraft failed soon after launch when it did not initiate subsequent burns necessary to leave Earth orbit for Mars. After many attempts to regain control, Phobos-GRUNT's orbit decayed and the probe reentered Earth's atmosphere in January 2012.

4.2. Gulliver (U.S. Discovery Program proposal for sample return)

The Gulliver mission, named for John Fielding's traveler who encountered Lilliputian astronomers discussing the moons of Mars, was proposed to NASA by a team led by Dr. Daniel Britt, the Jet Propulsion Laboratory, and the Lockheed Martin Corporation in the Discovery and Mars Scout competitions (Britt, 2003). The mission plan called for returning a sample from Deimos rather than Phobos, in order to minimize fuel requirements. Instruments include a high-resolution imaging camera for navigation and sampling site selection, a radar altimeter for closed-loop approach maneuvering, and a wide-angle descent imager to record the sampling site and the sampling process. Sampling would have been done using a touch and go technique that minimized spacecraft's interaction with the surface to collect a kilogram-sized sample of regolith. Because of the focused nature of the mission, remote sensing and in situ instruments were minimal and the bulk of the science would be derived from the returned sample. The sample return capsule would have reused a Stardust-like design, and returned to the Utah Test and Training Range (UTTR).

4.3. Aladdin (U.S. Discovery Program step-two proposal for sample return)

The Aladdin mission, named for its carpet-like sample collection system, was proposed to NASA by a team led by Dr. Carle Pieters, the Applied Physics Laboratory, and the Lockheed Martin Corporation in the Discovery competition (Pieters et al., 1999). The spacecraft would have entered a highly elliptical orbit around Mars that passed close to both Phobos and Deimos. Several flybys of each moon would have been used to refine knowledge of the moons' positions and to characterize sampling sites using high-resolution and multispectral imaging and visible/near-infrared spectroscopy. To collect one or more samples from each moon, at each opportunity the spacecraft would launch a cluster of projectiles to impact the target moon's surface, fly through the debris, and collect sample on a carpet-like pad. Successful interception of sample would be confirmed using a dust counter. Like Gulliver, Aladdin would have used a derivative of the Stardust sample return capsule and returned to Earth at the UTTR.

4.4. MERLIN (U.S. Discovery Program proposal for in situ science)

The Mars–Moon Exploration, Reconnaissance and Landed Investigation (MERLIN) was proposed to NASA by a team led by Dr. Scott Murchie, the Applied Physics Laboratory, and the Jet Propulsion Laboratory (Murchie et al., 2012). Only one of the two moons is targeted. The scientific objectives are to determine its elemental and mineralogical composition, to investigate its volatile and organic content, and to globally characterize the surface and processes that have modified it. These same measurements provide precursor information supporting future human exploration. An orbital payload would acquire global high-resolution and color imaging, putting the landing site in context. Radio tracking would characterize the gravity field and internal structure. The spacecraft would conduct remote sensing from a range of altitudes and illuminations over 4 months. Following the reconnaissance period, the spacecraft would land and obtain stereo imaging and measurements of elemental and mineralogical composition, and probe interior structure. The baseline landed operations period would be 90 days.

4.5. Hall (mission concept for sample return)

The Hall mission, named for American astronomer Asaph Hall who discovered the moons of Mars 1877, has been conceived by an international team led by Dr. Pascal Lee as a New Frontiers-class mission that would use solar electric propulsion to rendezvous with and sample both Phobos and Deimos (Lee et al., 2010). This mission was studied by the NASA Glenn Research Center and found to fit within the cost and scope of a New Frontiers-class mission. The nominal science payload includes a laser rangefinder, high-resolution color panoramic and microscopic imager, an APXS, a neutron detector/gamma-ray spectrometer, and a radiation dosimeter. The mission plan would be to land on and sample Phobos at least two locations, and to land on Deimos and sample at least one location. A total of 1 kg of regolith would be returned to the UTTR.

4.6. Comparison – science, complexity, and cost

The differences between these five mission concepts illustrate the cost trades for sample return, remote sensing, and in situ science as well as preparation for future human exploration. The three Discovery-class concepts (Gulliver, Aladdin, and MERLIN) are comparable in their total resources and complexity. MERLIN is able to address strategic knowledge gaps and the problem of one moon's origin by obtaining critical elemental and mineral abundance measurements in Table 1, at the cost of not fully addressing the second and third geochemistry goals outlined in Section 2. Aladdin and Gulliver each return samples and fully address the moon's origin and geochemistry goals, at the cost of minimizing global characterization. Phobos-GRUNT and Hall each complement remote sensing, in situ science, and closure of strategic knowledge gaps with return of samples. However, these more complete missions come at a cost of twice or more the funding required to implement a Discovery-class mission.

5. Conclusion

Returned samples have a proven track record of revolutionizing planetary science. The geochemical insights resulting from analysis of Phobos' regolith in terrestrial laboratories exceeds what would result from in situ and remote sensing missions. A Martian moon sample return can provide insight into primitive asteroids, and possibly sample Mars' Noachian crust to address questions of planetary evolution. The geochemical results are obtained through a tradeoff with in situ science and global characterization, if the resources available for a mission are fixed.

The moons of Mars remain a scientifically valuable target because understanding their origins illuminates early solar system history. Moreover, they are a potential source of resources or a base camp for future exploration of Mars. Although the failure of Phobos-GRUNT to complete its mission to Phobos was disappointing, future exploration of Phobos or Deimos remains a high science payoff objective that can be accomplished with existing technologies.

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