An Overview of Phobos and Deimos and their Exploration

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Abstract

Over the past 40 years of missions to Mars much has been learned about the many features of the planet and its two moons, Phobos and Deimos. Controversy surrounds the moons origins, physical characteristics and bulk composition. Their composition places important constraints on the moon's origins. Various researchers have postulated that Deimos and Phobos are of main belt genesis and of carbonaceous composition, whilst others have explored alternate origins and a composition more akin to ordinary chondrites. In concert with this, the curious surface features of both Deimos and Phobos, such as the groove formations, heterogeneous regoliths and albedo variances, have been investigated to gain insight into their surface morphology, composition, and evolution. Future missions to Mars should encompass Deimos and Phobos as outposts for the exploration of the red planet, as well as being a worthwhile mission objective in their own right. Such missions would provide unparalleled opportunities to study Deimos and Phobos in great detail and potentially support human Mars expeditions. In an effort to raise further interest in this goal and explore new possibilities, a hypothetical multi-function unmanned Phobos mission has been devised. The mission exhibits an alternative method to acquire a wide suite of comparative data from a number of collection vehicles, based on previous proposals and related studies.

Introduction

Over many decades much work has been undertaken to understand the many features of Mars and to gain insight into its two moons, Deimos and Phobos. Both moons have a curious relationship to Mars. Controversy surrounds their origin, physical characteristics and constituent chemistry. A number of remote sensing missions have visited the two moons and a myriad of data has been collected resulting in a deepening complexity of questions and ideas. Various arguments have been postulated to answer fundamental questions that prevail in relation to Deimos and Phobos. This paper aims to present what is currently known about the two moons and expose the major knowledge gaps and corresponding theories to provide an overall and up to date understanding of the Martian moons. Table 1 provides a detailed list of data on the orbital and physical characteristics of Deimos and Phobos.

Deimos the Outer Moon

Deimos, smallest of the two Martian moons, orbits the red planet outside the orbit of Phobos with a semi major axis of 23,460 km. Traveling at an average orbital speed of 0.22 km/s, Deimos also has a low eccentricity. The dimensions of Deimos are approximately measured to 15×12×10.4 km and the body carries a mass of 2.244×10^{15} kg. Deimos orbits in synchronous with Mars, rotating slowly and retaining a low surface gravity.

Table 1.

Orbital and Physical Characteristics of Deimos and Phobos.

	Deimos	**Phobos**
Dimensions	15×12×10.4 km	26.8×21×18.4 km
Mass	2.244×10^{15} kg	1.07×10^{16} kg
Density	2.2 g/cm3	1.9 g/cm^3
Surface Gravity	0.0039 m/s^2	0.0084-0.0019m/s^2
Escape Velocity	0.0069 km/s	0.011 km/s
Rotation Period	Mars synchronous	Mars synchronous
Albedo	0.07	0.07
Mean Surface temp.	≈233 K	≈233 K
Eccentricity	0.0002	0.0151
Orbital Period	1.262 d	0.318 d
Mean Orbital Speed	0.22 km/s	2.138 km/s
Inclination	27.58°	26.04°

Asaph Hall of the US state of Connecticut first observed Deimos in 1877 whilst observing Mars. Little could be deduced from early observations of the faint objects. It wasn't until the Mariner 9 mission of 1971 that Deimos was closely photographed and examined in greater detail. Images of a small planetesimal like object were sent back to Earth. Observers witnessed a smooth body with few features on the surface. Subsequent images of Deimos produced by the Viking and Phobos-2 missions provided higher resolution images and confirmed a near featureless body, with a smooth and sparsely cratered surface, though craters smaller in size relative to Phobos (*Thomas and Veverka 1980a*). Figure 1 exhibits an image captured by a Viking orbiter, clearly displaying these features.

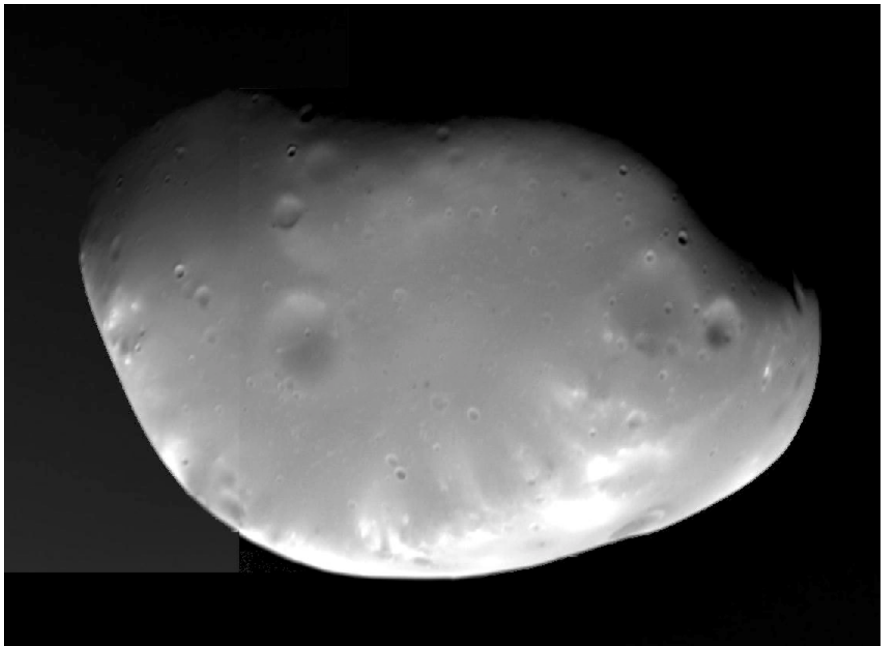

Figure 1. Composite photographs of Deimos captured by the Viking orbiter.

Phobos the Inner Moon

With a semi major axis of 9377.2 km, Phobos orbits Mars unusually close, just ~5000 km from its surface, with a mean orbital speed of 2.138 km/s. Phobos is the largest of the Martian moons measuring dimensions of around 26.8 × 21 × 18.4 km and amassing 1.07×10^{16} kg. Phobos exhibits a slightly higher eccentricity than Deimos, though this can be considered largely negligible when compared to other bodies in the solar system. As in the case with Deimos, Phobos remains in a synchronised orbit around Mars and as expected due to its relatively small mass and low rotational momentum, the surface gravity is quite low.

Phobos was discovered soon after Deimos, by Asaph Hall during observations of Mars in 1877. Along with the various tasks conducted close to Phobos by the Mariner 9, Viking probes, Phobos-2, Mars Global Surveyor and the recent Mars Express mission, a series of detailed images were captured of the moon. The Phobos images are striking. The body exhibited signs of heavy bombardment in the past with extensive cratering over much of the surface. Most notable of the craters is the Stickney crater, so named after Halls wife, measuring 11.3km in diameter. Phobos is dominated by a very dark surface and is interrupted by lightly coloured crater rims. In addition, linear grooves dug into the surface, most running perpendicular to the rotational axis and others radial in formation, are prominent over much of the body (*Murray et al 1994*).

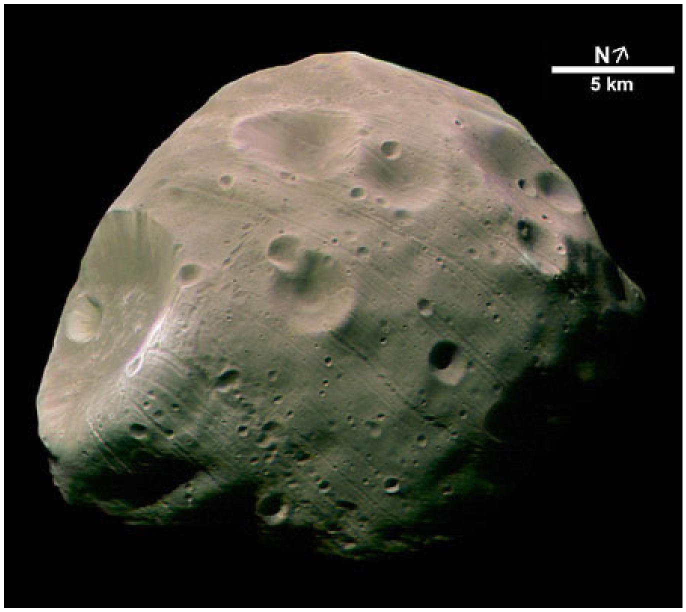

Figure 2. Photograph of Deimos from the Mars Express spacecraft. Note the heavy cratering and lateral groove formations.

Major Physical Characteristics of Deimos & Phobos

The Regolith of Deimos

Deimos displays a smooth, bright surface, lacking the distinctive large scale cratering and groove formations characteristic of Phobos (*Dobrovolskis 1982*). Its composition is speculative, though has been suspected to be of a carbonaceous chondrite nature. Observations of albedo occurrence show that bright material form streamers downslope from crater rims, indicating creep movement. The bright regolithic material seems to originate from exposed bedrock at these rims. The migration of regolith and surface ejecta (from previous impact events) along slopes has effectively wiped clean much of the crater topography. A chronology based on cratering is therefore difficult at best. Seismic shaking due to a large impact event, such as that experienced on Deimos at the southern hemisphere (11 x 9 km crater, relatively larger than Stickney crater on Phobos), could theoretically have disrupted emplaced regolith and ejecta (*Thomas et al 1996*). This may have resulted in the subsequent preferential migration of material downslope in accordance with prior topography. Infilling of craters and depressions equilibrated most of the surface landscape.

Whilst lighter material form streamers down gentle slopes on Deimos, the dominant material found along most of the surface and within craters is in contrast dark. *Thomas et al 1996* puts forward that material which infills crater basements was sourced from impact ejecta (*Thomas et al 1996*). This is strengthened by the observation of some well defined craters with high rims where infilling has taken place, though clearly material must have been inhibited from moving along the surface and over their rims (*Thomas and Veverka ,1980b*). *Thomas et al 1996* goes further to suggest that Deimos may have undergone a catastrophic impact event, resulting in the blanketing of the surface with unconsolidated debris, infilling existing craters. Deimos may retain large proportions of its ejecta (*Davis et al 1981*), unlike asteroid bodies, due to its gravitational relationship to Mars (*Thomas et al 1996*). The regolith cover on Deimos has been estimated to be around 10-20m in depth, and may be linked to the tidal (Mars) dissipation of the moon, which is inconsistent with a global surface rigidity (*Yoder 1981*).

Water on Deimos and Phobos

The greatest argument for water on Deimos and Phobos has been the discovery of the moons low densities in comparison with other bodies of their size within the inner solar system. Inferences on a water ice baring celestial body could account for a low density and support a main belt origin. If Deimos and Phobos retain substantial amounts of volatiles within their surface and internal structure then it could point to a thermally unaltered, mildly metamorphosed or aqueous altered compositional mineral assembly. The best analogues for minerals of this nature are ordinary and carbonaceous chondrite meteorites. Furthermore, the best spectral analogues for Deimos and Phobos include D, T and C class asteroids (*Rivkin et al 2001*). However, recent analysis of near-infrared spectrophotometry data raises new questions with regards to this earlier belief of hydrated Martian moons.

Rivkin et al 2000 points to the lack of detectable hydrated minerals at the surface of Deimos and Phobos. As an alternative explanation for their low densities, *Rivkin et al 2001* suggest the occurrence of macroporosity within surface materials (*Rivkin et al 2001*). However, there remains uncertainty with regards to the currently unobservable internal structure of these bodies. *Fanale and Salvail 1990* suggest a model whereby a theoretical internal ice body within Phobos would vaporise within 1km of the surface due to heat fluxes, from solar radiance and Mars reflectivity, and migrate toward surface loss and also to condensation sinks deeper in the moon over geological time periods (*Fanale and Salvail 1990*). This model may also be applicable for Deimos and would depend on its thermal state at a further distance from Mars.

If water can be found to exist as an ice phase on Deimos and Phobos, the scientific implications would be significant. Water would provide a vital clue to the current and past internal processes within the moons and offer vital evidence for their origin. Further to this, from an alternative perspective, in the long term Deimos and Phobos could potentially provide a strategically positioned source of H and O, useful in propulsion systems and within the human habitat for future Mars exploration. With lingering uncertainties regarding water retention on Deimos and Phobos, it would be prudent prior to serious Mars human exploration planning and execution to physically probe beneath the Martian moons surface to ascertain their true compositional nature. Remotely probing the surface of Phobos will be elaborated upon later in this paper.

The Composition of Phobos

The composition of Phobos is currently not completely agreed upon among researchers. The only past and current means available to study the surface properties of Phobos have been various photographic media and spectral techniques carried out from remotely operated probes and ground based observatories. There has still not been an attempt to retrieve a surface sample and return it to Earth. The Phobos-2 mission suffered a severe blow when the probe lost contact during important landing maneuvers and spectrophotometer and radiometer (KRFM) readings aimed at the Phobos surface in 1989. The data which was retrieved before communication was terminated is not of the standard which would have been achieved if the mission was fully successful. Nevertheless, it has been closely examined with published findings available (*Ksanfomality et al 1990* and *Ksanfomality and Moroz 1995*).

According to *Ksanfomality et al 1995, Murchie et al 1996, Rivkin et al 2001*, and *Simonelli et al 1997*, Phobos retains a heterogeneous surface composition, quite different from that expected of a primordial water retaining body. Early researchers of the Viking probe era had come to the initial conclusion that Phobos may have been homogeneous in composition and was best suited to analogous carbonaceous chondrite meteorites, though this has come to be challenged by subsequent work (*Rivkin, A. S. et al 2001*). More contemporary evidence extracted from revisions of the Phobos-2 spectral data, indicate at least two units existing as an anhydrous surface material. *Ksanfomality et al 1995* identify the existence of optically blackened ordinary chondritic material, and a second unit that is currently not analogous to any known meteorites. Alternatively, a mixture of accreted material ejected from the Martian surface by impacts may coexist with carbonaceous, ordinary chondrite and cosmic dust material. (*Ksanfomality et al 1990* and *Ksanfomality and Moroz 1995*).

A thermal infrared observation of Phobos' thermal inertia indicates that Phobos has a fine grained regolith blanketing its surface, similar to Luna regolith (*Ksanfomality and Moroz 1995*). According to *Simonelli et al 1997*, the regolith was emplaced and consequently modified during impact events, possibly leading to a decrease in surface density to 1.9 g/cm^3 (*Ksanfomality and Moroz 1995*). *Shkuratov et al 1990* go so far as to suggest that the dark regolith of Phobos, which exhibits a predominantly low albedo, may be of mafic or ordinary chondritic composition, space weathered by impacting solar particles, resulting in a darkening effect. This model may account for the occurrence of material with a higher albedo at the rim of craters, which may be excavated underlying material previously ill exposed to space weathering processes.

The composition of Phobos places important constraints on the moon's origin. If in fact, as will be discussed later in this paper, Phobos is a remnant of a larger ancient moon which possibly underwent differentiation, the materials on Phobos should reflect mineral assemblages which have undergone melting, fractionation and crystallization. Further revision of Phobos-2 infrared spectral data by *Gendrin et al 2005* does indicate the presence of olivine and low-calcium pyroxene, though the proportions and source of these ultramafic minerals is not certain. However, if Phobos is a captured body composed of carbonaceous material, then one can be lead to expect that Phobos originates from the region of the solar system where C class asteroids are thought to concentrate, the outer edges of the main belt. It is then a question of gravitational and orbital dynamics. The topic of origin will be discussed later in this paper. In any case, there remains the need to sample the moon as necessitated for conclusive and indepth understanding of the bodies enigmatic past (*Galeev et al 1996*).

Groove Formation on Phobos

One of the most obvious surface features of Phobos are the typically parallel trench like formations commonly referred to as grooves. Grooves can be observed commonly running perpendicular to the rotational axis of Phobos, but also running in radial formation from the Stickney crater. The most prominent grooves on Phobos have been estimated to measure 50-200 m wide and 5-20 m deep, with lengths of up to 20 km (*Horvath et al 2001*). A variety of ideas on their formation have been postulated and conclusions commonly conflict.

The possibility that grooves formed as a result of chain cratering from Mars ejecta has been put forward by *Murray et al 1994*. This model sees secondary cratering on Phobos as a result of string like ejected material sourced from large Martian impacts, so much so that Martian ejecta gains sufficient velocity to escape Mars atmosphere and strike the near orbiting moon. Martian impact ejecta striate Phobos' surface, creating indented linear trench like structures. *Murray et al 1994* argue that Phobos can be hit by Martian material from any direction, as indicated by the distribution of grooves globally. The fact that Deimos does not exhibit grooves has been accounted for, recognising the maximum velocity of material from Mars to be 4.5 km/s^{-1}, just low enough not to reach Deimos under Martian orbital dynamics. This finding adds to the suspicion that Phobos may retain valuable geological samples of Mars throughout vast epochs of Martian history. However, there may be some problems relating this process to an ancient Martian atmosphere which would be expected to be quite different to today's conditions. If a thicker, wetter atmosphere dominated past conditions on Mars, the implications for escape velocities may vary when compared to today's Martian environment (*Murray et al 1994*).

As an alternative, *Asphaug et al 1992* explain the effects of the Stickney impact event in terms of shockwaves diffusing throughout Phobos' internal structure resulting in fracturing. Fracturing may have displaced large sections of the body and caused the formation of lateral grooves on the surface at regularly spaced intervals. Grooves subsequently fill with regolith sourced from impact ejecta. However, for this model to work, Phobos must have a homogeneous composition otherwise the shockwaves from Stickney would scatter randomly and not concentrate in fractures. *Asphaug et al 1992* use both basalt and ice to simulate and model the effects of massive shockwaves to determine results for two possible extreme compositions for Phobos. Results show that the basaltic fracture model fits the current state of Phobos well. However, *Asphaug et al 1992* include that it would not be possible on the basis of their studies for Stickney to lower the density of Phobos as a whole, and that density is most probably compositional in nature (*Asphaug et al 1992*).

Horvath et al 2001 have proposed that the grooves on Phobos may be structural features, as a response to internal geological layering. *Horvath et al 2001* go further to suggest that structural grooves and remnant magnetism found on asteroids 951 Gaspra and 243 Ida may point to the two asteroids originating from a larger differentiated body. This in turn may be the case for Phobos, ruling out any influence of Mars for groove formation. Also, Gaspra and Ida lack large impact evidence such as Stickney, and therefore if confidence can be placed on asteroid analogues then grooves can not be of impact origin (*Horvath et al 2001*).

Stooke 2000 reports that faint pre-Stickney grooves were observed during a study of surface stratigraphy on Phobos, and suggests a disruption event during the proto moon to be the cause of these grooves. Other researchers have suggested Mars-moon tidal fluctuations or Mars ring interaction to bring about the groove formations (*Murray, J. B. et al 1994*). In any case, there seems to be a growing awareness that Phobos is not the only celestial body to have groove formations on its surface, as exhibited by Gaspra and Ida (*Horvath et al 2001*). A detailed close surface mission would be invaluable in shedding light on Phobos surface morphology.

Bright Crater Rims of Phobos

The surface of Phobos exhibits mixed albedo measurements, with lighter and darker regolith defined in certain regions. *Shkuratov et al 1990*, with the aid of Phobos 2 imagery, finds that regolithic material located at the rims of minimally degraded craters and grooves has a higher reflectance than surrounding regolith plains. It has been interpreted that craters showing a low amount of degradation are of a younger age. Therefore, material displaying a higher albedo may be related to younger impact events, as opposed to darker, older material. In a currently unknown relationship, this may be the case for grooves, however their origin remains highly speculative. The surrounding darker regolith may have darkened over time due to weathering by solar particles (*Shkuratov et al 1990*).

This hypothesis is supported by two related examples. Firstly, lunar regolith of younger age retains a higher albedo, and regolith of an older age is darkened. This relationship is thought to be the result of micrometeorite impact and solar wind processes. Secondly, ordinary chondritic material has been found to darken via space weathering until it resembles carbonaceous chondrites in albedo. This latter point would allow Phobos to have an ordinary chondrite composition (*Shkuratov et al 1990*). If lighter regolithic material is indicative of less exposure to surface dynamics, then it may be inferred that this same material represents possibly unaltered (albeit, less altered) internal samples of Phobos, excavated from impacts. If this is the case, then regolith displaying higher albedo may give the best insight into Phobos' internal composition and structure.

Origin and Fate

As alluded to earlier in this paper, the origin of the Martian moons is currently undetermined. However much of the research into what is known about Deimos and Phobos has lead to two main theories of origin. The first and most popular hypothesis proposes that the moons are captured asteroids from the main belt. This premise is commonly based upon the similar shape and colour of Deimos and Phobos to main belt bodies. Also, Mars neighbors the main belt and seems to be a likely candidate for perturbing nearby objects via its gravitational influence. The second involves the formation of Deimos and Phobos in Mars orbit itself . It has been proposed that Deimos and Phobos may have fragmented from a passing asteroid in Mars orbit or that Mars even harbored a single, larger moon, not unlike Earth's, which was fragmented, leaving

Deimos and Phobos as left over remnants. Alternatively, dust may have accreted to form a parent body for Deimos and Phobos in orbit around Mars. It can not currently be ruled out, however, that the two moons have different origins all together.

In the case that Deimos and Phobos were captured from the main belt, it follows that asteroid analogues for the composition of the moons should exist among the asteroids. However, insight into the Martian moons composition is currently ambiguous, though this has not prevented their approximate comparison to known meteorite material via spectral matches. The surface of Phobos has been likened to ordinary chondrites that have been darkened by space weathering and regolith processes. Spectral data for ordinary chondrites match the Phobos-2 surface data well. Previous to this it was strongly argued that Phobos' surface was primarily of carbonaceous chondrite composition (*Ksanfomality and Moroz 1995*).

Meteorite analogues are significantly important because they can be approximately matched to classes of asteroid bodies on the basis of spectral data. Because asteroid classes generally populate certain areas of the main belt, approximate regions of the main belt can be narrowed down as sources of particular meteorites. For example, C class asteroids such as 1 Ceres generally linger in the outer main belt, and are the likely parent bodies of carbonaceous chondrite meteorites. Hence, this same process may be extended to Phobos and Deimos, where meteorite material may provide a suitable link to the main belt.

Phobos and Deimos display low eccentricities and rotate in synchronous with Mars, and Phobos in particular travels very close to the surface of Mars with ever degrading altitude. On examination of current orbital characteristics it can be inferred that the capture scenario is unlikely for both satellites. However, mathematical modeling undertaken by *Cazenave et al 1980* provides some clues as to the precession of the moons. It was found that Phobos did originally have a highly eccentric orbit around Mars close to the solar system plane of the ecliptic, rather than its current position at the host planets equator. This type of early orbit can be construed as characteristic of an orbital capture scenario. Modeling, however, does remain somewhat more uncertain for Deimos, though does bring about the view that Deimos must have been captured after Phobos otherwise a collision would have been inevitable (*Cazenave et al 1980*).

Further modeling conducted by *Szeto 1983* finds problems with two separate asteroid bodies being captured by Mars. *Szeto 1983* raises the point that to capture a body from a heliocentric orbit and transfer its trajectory to a planetocentric orbit would require Mars tidal effects to reduce the body's energy levels significantly. Although this is viewed as unlikely by *Szeto 1983*, he does give credence to the idea that Deimos and Phobos may have been part of one larger body. *Szeto 1983* suggests that it may be possible for one large asteroid body to have passed through or broken up prior to the orbital influence of Mars, and became fragmented by some mechanism near or within the Roche limit, leaving Deimos and Phobos as remnant bodies. In this case the larger mass may have escaped or crashed down to the Mars surface. However, *Szeto 1983* adds that these scenarios do not accurately account for the very different orbital positions of the two moons, nor to the lack of collision between them.

Elaborating further on the modeling posed by *Szeto 1983*, *Hartmann et al 1975* earlier work explores the possibility that one moon, between around 800km and 1500km radius, may have existed in orbit around Mars sometime in the past. This idea is essentially put forward to account for the possible angular momentum deficiency of Mars. According to *Hartmann et al 1975*, Mars maintains a longer rotation on its axis than would be expected for a planet of its size with relatively small satellites. Mars has a similar rotational period to Earth, though Earth's angular momentum is in part due to the moon's tidal influence. *Hartmann et al 1975* further adds that a large scale accumulation of dust particles from the main belt could affect the angular momentum of Mars on impact with the planet or could contribute to the accretion and formation of a large moon.

Various models can be devised to account for the fragmentation of a theoretical early Martian moon, leading to leftover products in the form of Deimos and Phobos. However, if this is to be accepted, then attention must also be focused on the compositional relationship between an early moon and Deimos and Phobos. A Martian moon modeled on Earth's moon would have undergone global differentiation, or, as *Szeto 1983* suggests in his work, Deimos and Phobos could be fragments of large bodies containing ice mantles of a primordial origin (*Szeto 1983*). Either model would place significant constraints on the current composition of Deimos and Phobos.

Many uncertainties plague notions of origin for Deimos and Phobos, so far adding to the lack of irrefutable answers for their formation. Yet, less uncertainty is afforded to their fate. Orbital calculations see Deimos slowly spiraling away from Mars, while in contrast, Phobos is rapidly heading towards fragmentation or a crash landing. It is estimated that at an orbital shifting rate of around 1.8m per century, Phobos will enter the Roche Limit in approximately 50 million years and breakup, possibly forming a circum Martian ring. Alternatively, Phobos may impact with the surface of Mars within a similar time span. Deimos, however, orbits at a greater distance from Mars and is expected to recede under the influence of the primary's tidal forces. Their orbital differences may be linked to their separate origins.

The Significance of the Martian Moons

A better understanding of the nature and history of Deimos and Phobos might significantly improve our understanding of the Martian orbital environment, and, potentially, even processes going back to the solar nebula. The discovery of their composition alone would provide invaluable information about the two moons formation processes and source environment within the solar system (*Rahe et al 1999*). This is supported by the possibility that Deimos and/or Phobos may currently be the most easily accessible asteroid bodies in the solar system. Furthermore, the moons may provide examples of the primordial material from which Mars was assembled. It is suspected that Phobos may also be a repository of Martian samples accreted onto its surface after having been ejected from Mars. In addition to advances into morphological and evolutionary knowledge, Deimos and Phobos potentially play a significant role in establishing a foothold for the human exploration of Mars. Deimos and Phobos could pose as strategically positioned refueling, supply, control and research epicenters for Mars expeditions into the future.

Given these opportunities, Deimos and Phobos play two major roles for human space exploration; 1. As catalysts to understanding the formation, processes and prospective resource availability of small bodies inside the main asteroid belt or in Mars orbit. 2. As space borne platforms, realistically accessible by current technological standards, providing an environment opportunely suitable for anchoring and conducting mission support activities for both moon and Mars exploration. Both these roles encompass the pursuit of a greater understanding of Deimos, Phobos and Mars. With the successful execution of future Deimos/Phobos exploratory missions, it is hoped that many of the knowledge gaps that exist today will no longer prevail.

The Exploration of Phobos and Deimos

Past Missions to Phobos and Deimos

The first of a succession of missions that have collected data on the moons of Mars began in 1969 with the flybys of Mars by NASA's Mariner 6 and 7 spacecraft. These missions showed that Phobos was composed of very dark material and was somewhat elongated in shape. In 1971 Mariner 9 conducted the first close flyby of Phobos. Mariner 9's primary goal was to photographically map the surface of Mars, measure various global features (ie. shape and oblation etc) and obtain spectral data. Secondary to this was to provide imagery of Phobos. The mission was deemed a success, though early images of Phobos were of poorer quality in comparison with later missions. Mariner 9 remained in operation for well over a year, ceasing communication in 1972 (*NASA 2006*). Four years later a new series of orbiter missions would take the reins under an additional NASA venture, producing images that would reveal more clearly the Phobos surface.

Viking 1 was launched in 1975, to be closely followed almost a year later by Viking 2. Both craft were identical in design, carrying an orbiter craft and lander vehicle. Whilst primary interest was concentrated on the Mars landings, both Viking orbiters carried out crucial maneuvers that ensured their encounters with Phobos as part of mission objectives. Viking 1 made a close flyby of Phobos in 1976, followed by Viking 2 in 1977. The Viking orbiter resumes include the discovery of low surface densities for both Phobos and Deimos and a collection of detailed imagery of the heavy bombardment and striating groove formations on Phobos. The orbiters continued collecting data where Mariner 9 left off, measuring the atmospheric water and IR thermal activity on Mars (*Hamilton 2006 and NASA 2006*). Later photometric studies of the Phobos surface would take place using Mariner 9 and Viking orbiter imagery (*Simonelli et al 1997*).

After final transmission from Viking 1 in 1982, and prior to this Viking 2's cessation in 1980, another six years would come to pass before further close observation and remote sensing of Phobos would take place again. Phobos 1 and 2 spacecraft would represent a new generation of Russian unmanned craft, to supersede the earlier spacecraft of the Soviet Venera missions. Their launch took place in 1988, and it was hoped that both craft would vastly compliment previous missions. However, Phobos 1 experienced critical software failure enroute to Mars. This left Phobos 2, which differed from all other missions because it included a unique lander package destined for the surface of Phobos. This included two landers used for in situ regolith analysis (*Sagdeev et al 1987*).

The main objectives of the Phobos segment of the mission encompassed CCD image capture, radiophysical probing and ultraviolet, visible (KRFM) and near infrared (ISM) spectrometer sensory acquisition (*Murchie and Erard 1996)*. Phobos 2, after its circum navigation of Mars, was to exercise an approach orbit to approximately 50m above the Phobos surface and deploy the lander package, however during critical maneuvering the orbiters main onboard computer malfunctioned and communication was lost at a distance of 200km. Further attempts to retrieve the spacecraft were terminated March of 1989 and the mission was deemed a moderate success. Imagery and spectral data were obtained from a narrow remote sensing track at 200km distance which has subsequently undergone analysis and revision with published findings available (*Ksanfomality et al 1990, Ksanfomality and Moroz 1995, and Murchie and Erard 1996*).

During 1996 NASA launched its Mars Global Surveyor (MGS) spacecraft which reached Mars the following year. Utilising sophisticated sensory equipment, including the Mars Orbiter Laser Altimeter (MOLA), MGS's primary objectives were to study the atmosphere, surface and interior of Mars. One of the highlights of resultant data acquisition included the 3D modeling of the north polar ice cap on Mars. In addition to its primary functions, MGS captured near surface imagery exhibiting more clearly than previous missions the intricate surface features of Phobos. Observations provided the opportunity to ascertain geomorphological aspects of Phobos and determine the existence of an approximately 1m thick fine grained regolith blanketing the surface. MGS is still operational and continues to perform limited tasks ten years after its initial launch (*NASA 2006*).

The European Space Agency (ESA), in conjunction with NASA and the Italian Space Agency, launched a new orbiter mission during mid 2003 named Mars Express. The mission was ambitious and the craft was made up of an orbiter craft and lander vehicle. The main objectives for the orbiter were to search for subsurface ice on Mars and study the planets atmosphere and surface geology. The highlight of the mission included the landing vehicle, so named Beagle 2, which was equipped to carry out exobiology research on the Martian surface and search for signs of life (*ESA 2006 and NASA 2006*). To the disappointment of many within the scientific community the lander ceased communication during its descent. However, the High Resolution Stereo Camera (HRSC) and Super Resolution Channel (SRC) panchromatic framing camera fitted to the Mars Express orbiter have thus far captured the sharpest imagery of Phobos at distances between 5000 km to 150 km. Observational data has enabled the topographic mapping of Phobos, and obtained astrometric measurements ascertaining the satellites position, whilst improving on accuracy of data collected from previous missions. In addition, the HRSC captured imagery of the shadow of Phobos passing over the surface of Mars, consequently combined with MOLA data, and used to correct the satellites ephemeris data. The Mars Express orbiter is currently slated to continue observing Phobos with the

HRSC and SRC instruments in addition to its primary mission functions (*Oberst et al 2006*).

The Future of Phobos Exploration

Only recently a new orbiter has reached Mars orbit and has continued aero-braking in the thin upper Martian atmosphere since insertion in March of 2006. The Mars Reconnaissance Orbiter (MRO), a NASA initiative, will soon be preparing to record various data as part of its mission program. The objectives of the mission encompass the continuation of the search for life on Mars, the study of climate and surface features of the planet, and additionally assess resource availability (*Graf et al 2005 and NASA 2006*). As with other missions with a primarily Martian objective, MRO will be in close range to Phobos after aero-braking and will be directed to test the functionality of some of its various instruments on the satellite. This will include highly sophisticated camera hardware which is expected to capture imagery far clearer than earlier spacecraft (*West, M. Personal Correspondence, 2006*).

Various hypothetical missions have been explored for more in-depth study of Phobos, though currently only one mission continues to show some promise for deployment within the near future. The Russian designed Phobos-Grunt mission (PGM) is a fully dedicated mission to seek out the compositional nature of Phobos by extracting a soil sample from its surface and returning to Earth for analysis. This is a highly ambitious undertaking for Russia's space research program, especially after the loss of "Mars 96" and Phobos-2 in previous years. Possible delays for launching the mission may hamper prospects of obtaining fresh samples of Phobos' regolith in the immediate future, though a tentative launch is slated for 2009 (*Marov et al 2003*). Though, if the mission does get off the ground and becomes a success it will contribute significantly to the study of Phobos now and into the long term future.

The PGM is essentially a sample return mission, never before undertaken on Phobos, though technically feasible. The PGM would see the spacecraft cruise to Phobos using electric propulsion provided by solar panels after LV (launch vehicle) and chemical propulsion separation, used for Earth-Mars transfer initiation. Subsequent maneuvering into Mars orbital insertion and a Phobos approach would follow. Final hard docking with the Phobos surface, using a Phobos-specific mooring system and engine stabilizers, would position the lander for soil extraction. The PGM lander could utilise a number of instruments, including those from previous lander missions, to carry out in situ surface measurements and experiments. Extracted soil is inserted into an Earth bound return delivery system, providing the necessary thrust for Mars-Earth transfer and an Earth orbital insertion. Final atmospheric re-entry and retrieval of the soil container would complete the mission (*Marov et al 2003*). The "Aladdin" project submitted to NASA outlined a similar sample return mission in 1999 (*Pieters et al*). However, difficulties experienced by the Hayabusa mission to asteroid Itokawa means that such missions should be regarded as both risky and difficult (*JAXA 2006*).

The near future will see the continuation of unmanned craft visiting Mars and its moons, collecting data that will eventually pave the way for human exploration. Phobos should play an important role in initial human exploration of the Martian system. This fascinating satellite presents a unique theatre of discovery, a potential source of natural resources and, of great importance, may be utilized as a space borne platform suitable for anchoring and conducting mission support activities for both moon and Mars exploration. *Singer 1999* discusses the integration of a Deimos and Phobos stop over during a human expedition to Mars, whereby the moons would provide an opportune environment for Martian sample analysis and water extraction, if water is present. In addition, Phobos could function as a communications and remote control centre for rovers and related equipment at Mars surface. Delta *v* calculations deem Phobos to be a significantly easier target to reach than Earth's moon, therefore by current technological standards Phobos is at present a realistic goal for human visitation (*Singer 1999*).

Possible Multi-Function Phobos Mission

This section will outline a hypothetical multi-function unmanned Phobos mission aimed at the efficient and comprehensive study of the moons surface and internal properties. The data and design for such a mission is based on unique ideas combined with previous proposals and related studies (*Baker et al 2005*, *Hildebrand et al*, *Marov et al 2003*, *Pieters et al*, *Rahe et al 1999 and Walker et al 2005*). A three stage approach will be presented, additionally discussing planetary transfer and the overall mission plan. The mission would allow for the correlation of data between the three stages, which are composed of an orbiter control spacecraft, a lander laboratory (which has been configured to include a sample return module) and a surface penetrator. For this mission, Deimos will be added to the flight plan and orbiter objectives so as to widen the scope of exploration and insure the prospect of later data comparison between the two moons.

Planetary Transfer

A common aim in unmanned spacecraft design is to minimize total mass of the vehicle as much as possible for cost and lift/momentum efficiency. The difference between LV costs can be from $10M to $50M, depending on the choice of LV capable of lifting the necessary cargo (*Baker et al 2005*). Therefore, it becomes necessary to maintain light weight scientific instrumentation and propellant provisions within the spacecraft itself. New innovations in micro-satellite technology and ion and plasma propulsion systems do offer a light weight solution. A mission going beyond LEO (Low Earth Orbit) and following a minimum energy trajectory path to Mars, would only require slight continual adjustments to maintain course, for which small ion and plasma propulsion systems would be practical.

Electric current supplied by fixed solar panels have been found to be adequate during various phases of previous missions to Mars. Nuclear and large scale chemical propulsion systems can add significantly to cost and bulk, and therefore are not considered in this mission model. However, for some segments of the mission, including Mars/Phobos orbital insertion, escape and Earth orbital return insertion, provisional chemical propellant will be required for added propulsion during these maneuvers. The easiest planetary transfer path, requiring the least propellant expenditure is obtained in a heliocentric orbit, similarly planned for NASA's Dawn spacecraft destined for the main asteroid belt (*Dawn 2006*). However, the time lapse for such a path is considerably longer than Hohmann transfer orbits. Hence, mission objectives must be balanced between time-to-destination affordability and propellant to mass ratio constraints. In addition, Aero-braking would not be required if Phobos orbital insertion was controlled by a slow spiral and low energy thrusting, though could be factored in if later necessitated.

Orbiter

The orbiter craft would ultimately act as a control, communications and transport hub for all components of the mission. Minor velocity and directional adjustments during transfer and orbit phases of the mission would be controlled by an ion propulsion system within the body structure, which includes avionics (*Walker et al 2005*). The orbiter body structure would then be mounted on a chemical propulsion system suited for insertion and escape velocity control. An onboard computer and communications system (COM_2), and electrical power system is integrated into the orbiter body structure, separately compartmentalised. Internal and external sensory fixtures, such as multi-spectral camera, antennae and dust counter hardware, are wired and permanently fixed to the orbiter structure via an external platform. Two retractable solar panels are fixed to the COM_2 and electrical compartment. Figure 1. illustrates the orbiter schematic.

The orbiter body would act as a deployment platform for the lander and penetrator vehicles, and would return a sample of Phobos to Earth. A range of remote sensing equipment would be fixed to the external instrument platform, including:

- Multi-spectral camera
- TV camera
- X-ray, IR, NIR, *n* spectrometer
- Radio system
- Laser Altimeter
- Magnetometer
- Radar
- Dust Counter

Overall mass, without the lander and penetrator vehicles, according to figures calculated for a similar orbiter by *Walker et al 2005*, comes to a total wet launch mass of around 320kg. *Walker et al 2005* estimates include a 50kg payload, which may differ, depending on the incorporated instrumentation and their configuration. This also has implications for the provision of chemical propellant.

Lander

The lander has three main objectives; to carry out in situ measurements and experiments on surface regolith, measure seismic waves from the penetrator impact and obtain and return to the orbiter a soil sample. These objectives can be achieved with a multi-tasking lander, designed specifically with analytical instruments and a scoop-return mobile module. The lander body would be made up of a cylindrical structure, encasing a small chemical propellant cell, extendable solar panels, an instrument chamber with access to the external environment, a seismometer and a soil extraction/rocket deployable module to be reacquired by the orbiter. On deploying from the orbitor, the lander will boot a small onboard computer and communication system for navigation and data uplink, initially running on auxiliary battery power. Propellant would need to be expended for initiating and stabilising the landers descent for docking with the surface of Phobos. Once the landing has been achieved, solar panels would unfold and scientific instruments would begin automated tasking. A suite of scientific instruments would be useful in studying the surface properties of Phobos. Those chosen for this mission include:

- Panoramic Camera
- Alpha – X-ray – Gamma ray spectrometer
- Mossbauer spectrometer
- Gas Analyser
- Microscope Camera
- Radio System
- Seismometer
- Sun Sensor
- Soil Sampler

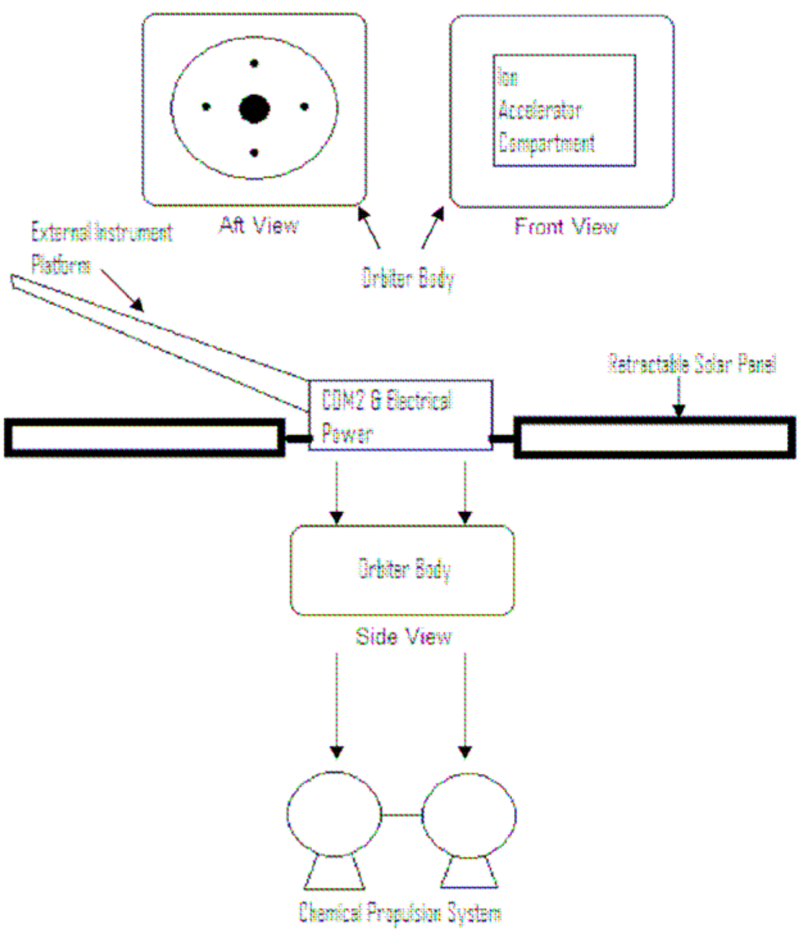

Figure 1. Illustrated schematic of the orbiter body with basic navigation, communication and power components.

Additional instruments or experiments may be added to the lander payload, though this would be constrained by overall mass and thrust effectiveness in accordance. Lander mass estimates do not exist at this time. Figure 2. illustrates a schematic of the lander and orbiter.

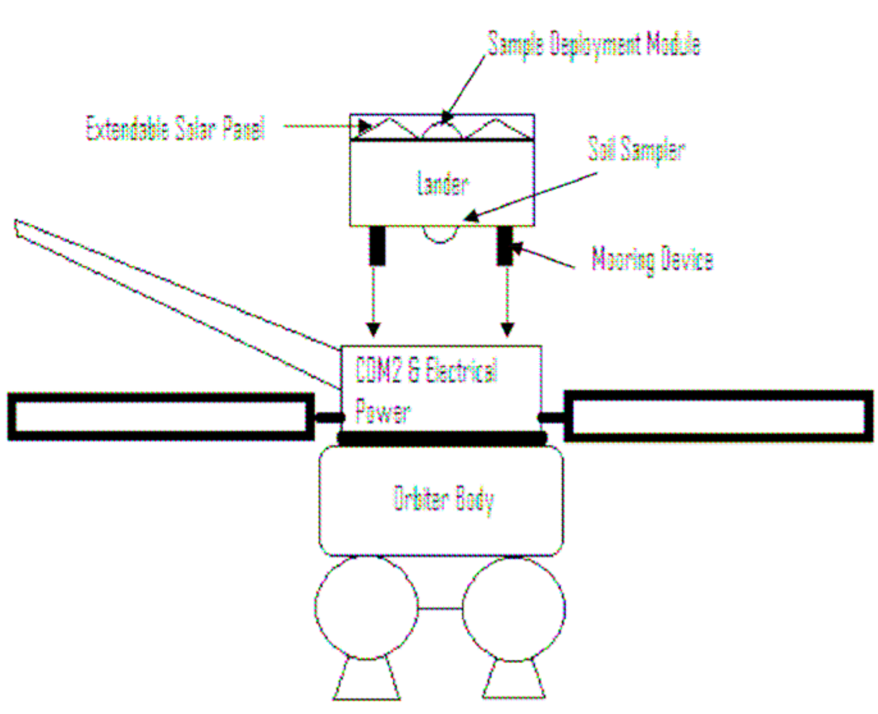

Figure 2. Illustrated schematic of the lander vehicle and its mounting position on the orbiter.

Penetrator

Penetrators are not a new concept in unmanned spaceflight (*Lorenz et al 1999*), though have yet to be actively demonstrated successfully under real mission conditions. Currently some mission models are including penetrator systems within their spacecraft design in anticipation of their use in future missions (*Walker et al 2005*). The penetrator used in this mission essentially aims to fulfill two objectives; to breach surface material and infiltrate subsurface stratum with the aim of conducting analysis on its properties and structure, and to cause sufficient subsurface seismic waves to be detected by the lander seismometer. Figure 3. illustrates a schematic of the penetrator and its orbiter mounting position.

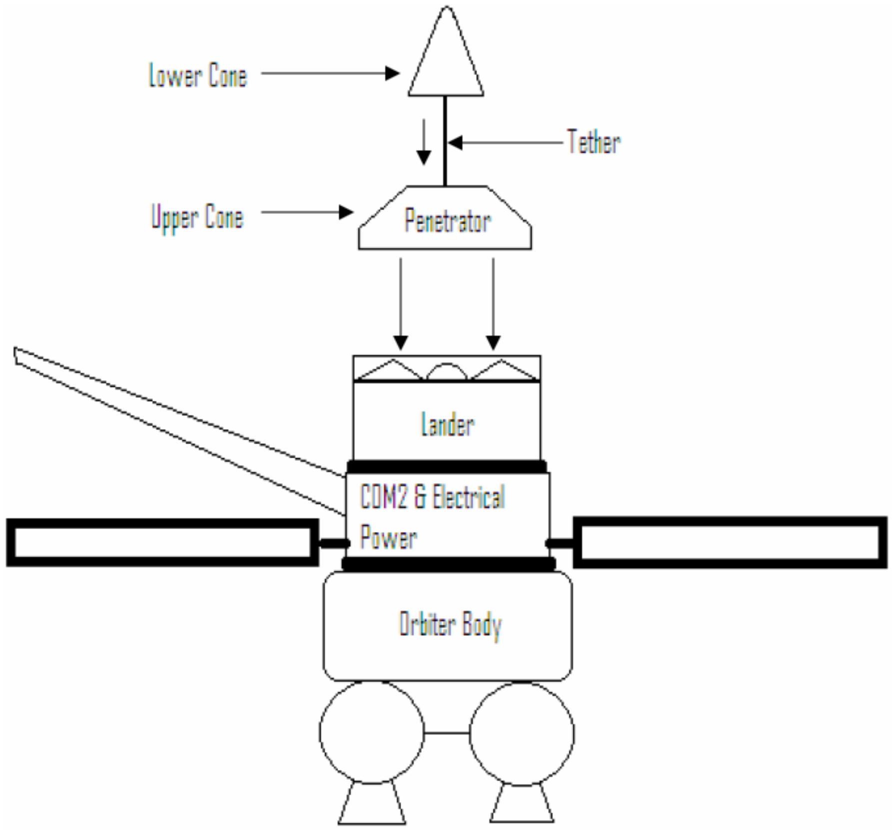

Figure 3. Illustrated schematic of the penetrator as it is mounted upon the lander vehicle.

The penetrator would be composed of a small propulsion cell and various thrusters, navigational and instrumental computer system, communications system, battery cell and scientific hardware, encased in a reinforced, armor piercing cone. The base (upper cone) of the cone would house the propulsion cell, battery cell, communications system and computer hardware. The lower section (lower cone) would contain the scientific hardware and data relay system connected to a tether, linking with the upper section. The upper and lower cone sections remain connected whilst in transit, when impact occurs the upper cone wedges nearer the surface whilst the lower section continues until the slack on the tether is diminished.

Depending on the actual dimensions of the penetrator and the amount of shock in which certain instruments can sustain, the total suite of scientific apparatus chosen for this mission are as follows:

- Alpha – X-ray – Gamma ray spectrometer
- Water Content Analyser
- Gas Analyser
- Temperature Analyser
- Neutron Detector
- Aft Camera
- Laser Environment Sensor

Walker et al 2005 devise content and mass calculations for a surface penetrator payload, including the above instruments, to be used on Mars. Their estimations conclude that one penetrator will have a total mass of 1.45 kg, including contingency (*Walker et al 2005*). Mass and size of the penetrator may vary, depending on the mission parameters, surface material and impact environment.

Mission Plan in Brief

A three stage mission consisting of an orbiter, lander and penetrator offers the prospect of acquiring a wide scope of data which may be evaluated and compared from three perspectives. A broad collection of data may also serve as a data acquisition contingency should any segments of the mission fail. The mission itself is ambitious and may present unforeseen difficulties. Though, the successes of previous orbiters to reach and circum-navigate Mars and deploy landers adds confidence that such a mission would succeed for Phobos. The following list provides a general breakdown of mission maneuvers and tasks during operation:

- Orbiter separation from LV and chemical propulsion burn to Earth-Mars transfer insertion.
- Ion propulsion thrusting during heliocentric orbital transfer path.
- Trajectory on course for a slow spiral to Deimos orbital insertion, with short burst thrusting for velocity reduction using chemical propulsion.
- At 200km to 50km orbiter instruments initiate and collect remotely sensed data (see Orbiter section) from Deimos surface.
- Short chemical propulsion burn to initiate Phobos orbital insertion.
- Orbiter instruments initiate collecting data from the surface of Phobos from 200km.
- Penetrator and lander deployed at 200m altitude above Phobos and communications uplink is accomplished, running on battery power.
- Lander proceeds to thrust and maneuver to dock with the surface of Phobos. Solar panels extend and on board scientific instruments initiate tasking and seismometer activates.
- Penetrator follows orbiter path, revolving once around the moon and shifting to 100m over target site, then beginning a full thrust burn to impact with the target site (1-5km from lander site), followed by onboard instrument initiation.
- Orbiter circum-navigates Phobos and proceeds to an altitude of 50m.
- Lander sample deployment module launches and docks with orbiter during flyby.
- Orbiter thrusts to escape velocity using chemical propulsion and inserts into Mars-Earth transfer, ion propulsion exploited for transfer, and chemical propulsion again for Earth orbital insertion.
- Sample deployment module is jettisoned from the orbiter and maneuvers to re-entry window, entering Earths atmosphere and parachuting to retrieval zone.

The time line for the mission is not completely certain. Based upon *Walker et al 2005* a one way twenty four month mission, including two months at Deimos and Phobos (*Walker et al 2005*), it is estimated that this mission would likely require forty six months, from LV separation to sample retrieval. However, data retrieved from the orbiter, lander and penetrator would be received at Earth in twenty two to twenty four months into the mission.

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References

Asphaug, E. and Melosh, H. J. 1992. *The Stickney Impact of Phobos: A Dynamical Model.* Icarus 101, pp. 144-164.

Baker, A. M., da Silva Curiel, A., Schaffner, J. and Sweeting, M. 2005. *"You can get there from here": Advanced low cost propulsion concepts for small satellites beyond LEO.* Acta Astronautica 57, pp. 288-301.

Cazenave, A., Dobrovolskis, A. and Lago, B. 1980. *Orbital History of the Martian Satellites with Inferences on Their Origin.* Icarus 44, pp. 730-744.

Davis, D. R., Housen, K. R. and Greenberg, R. 1981. *The Unusual Dynamical Environment of Phobos and Deimos.* Icarus 47, pp. 220-233.

Dawn: A Journey to the Beginning of the Solar System. Website: www-spc.igpp.ucla.edu/dawn Accessed 27/05/2006.

Dobrovolskis, A. R. 1982. *Internal Stresses in Phobos and Other Triaxial Bodies.* Icarus 52, pp. 136-148.

ESA: Mars Express. Website: http://sci.esa.int/science-e/www/area/index.cfm?fareaid=9 Accessed 26/05/2006.

Fanale, F. P. and Salvail, J. R. 1990. *Evolution of the Water Regime of Phobos.* Icarus 88, pp. 380-395.

Galeev, A. A., Moroz, V. I., Linkin, V. M., Zakharov, A. V., Basilevsky, A. T., Surkov, Yu. A., Akim, E. L., Duxbury, T., Kremnev, R. S., Martynov, B. N. and Papkov, O. V. 1996. *Phobos Sample Return Mission.* Adv. Space Res. Vol. 17, No. 12, pp. 31-47.

Gendrin, A., Langevin, Y. and Erard, S. 2005. *ISM observation of Phobos reinvestigated: Identification of a mixture of olivine and low-calcium pyroxene.* Journal of Geophysical Research, Vol. 110.

Graf, J. E., Zurek, R. W., Eisen, H. J., Jai, B., Johnston, M. D. and DePaula, R. 2005. *The Mars Reconnaissance Orbiter Mission.* Acta Astronautica 57, pp. 566-578.

Hamilton, C. J. 2006. *Views of the Solar System: Project Viking Fact Sheet.* Website: www.solarviews.com/eng Accessed 25/05/2006.

Hartmann, W. K., Davis, D. R., Chapman, C. R., Soter, S., Greenberg, R. 1975. *Mars: Satellite Origin and Angular Momentum.* Icarus 25, pp. 588-594.
Horvath, A., Almar, I. and Illes-Almar, E. 2001. *Comparison of the Surface Grooves on Gaspra and Phobos.* Adv. Space Res. Vol. 27, No. 8, pp. 1489-1492, 2001.

Hildebrand, A. R., Spencer, H., Carroll, K. A. and Zee, R. E. (Unpublished Paper) *PARTI (Phobos Advanced Rendezvous, Touchdown and Impacts): Martian Moon Exploration with Microsatellites.* Department of Geology and Geophysics, University of Calgary, Canada.

Ksanfomality, L., Murchie, S., Britt, D., Duxbury, T., Fisher, P., Goroshkova, N., Head, J., Kuhrt, E., Morov, V., Murray, B., Nikitin, G., Petrova, E., Pieters, C., Soufflot, A., Zharkov, A. and Zharkov, B. 1990. *Phobos: Spectrophotometry Between 0.3 and 0.6 um and Ir-Radiometry.* Planet. Space Sci., Vol. 39, No. 1/2, pp. 311-326, 1991.

Ksanfomality, L. V. and Moroz, V. I. 1995. *Spectral Reflectivity of Phobos' Regolith within the Range 315-600 nm.* Icarus 117, 383-401 (1995).

Lorenz, R. D., Moersch, J. E., Stone, J. A., Morgan Jr, A. R., Smrekar, S. E. 1999. *Penetration tests on the DS-2 Mars microprobes: penetration depth and impact accelerometry.* Planetary and Space Science 48, pp. 419-436 (2000).

Marov, M. Ya., Avduevsky, V. S., Akim, E. L., Eneev, T. M., Kremnev, R. S., Kulikov, S. D., Pichkhadze, K. M., Popov, G. A. and Rogovsky, G. N. 2003. *Phobos-Grunt: Russian Sample Return Mission.* Advances in Space Research Vol. 33, pp. 2276-2280.

Murchie, S. and Erard S. 1996. *Spectral Properties and Heterogeneity of Phobos from Measurements by Phobos 2.* Icarus 123, 63-86 (1996).

Murray, J. B., Rothery, D. A., Thornhill, G. D., Muller, J. P., Iliffe, J. C., Day, T. and Cook, A. C. 1994. *The origin of Phobos' grooves and crater chains.* Planet. Space Sci., Vol. 42, No. 6, pp. 519-526, 1994.

NASA: Mars Exploration Program. Website: www.mars.jpl.nasa.gov/missions Accessed 25/05/2006.

Oberst, J., Hoffmann, H., Matz, K. D., Roatsch, T., Wahlisch, M., Giese, B. and Neukum, G. 2006. *New Observations of Phobos and its Shadow with the HRSC/SRC on Mars Express.* Lunar and Planetary Science 2006. Website: www.lpi.usra.edu/meetings/lpsc2006/pdf/1312.pdf Accessed 24/05/2006.

Pieters, C., Calvin, W., Cheng, A., Clark, B., Clemett, S., Gold, R., McKay, D., Murchie, S., Mustard, J., Papike, J., Schultz, P., Thomas, P., Tuzzolino, A., Yeomans, D., Yoder, C., Zolensky, M., Barnouin-Jha, O. and Domingue, D. *Aladdin: Exploration and Sample Return of Phobos and Deimos.* Lunar and Planetary Science. Website: www.lpi.usra.edu/meetings/LPSC99/pdf/1155.pdf Accessed 25/05/2006.

Rahe, J., Mukhin, L., Sagdeev, R., Karavasilis, K., Trombka, J., Zakharov, A., Medvedev, A., Khatulev, V. and Yuriev, V. 1999. *Low Cost Mission to Phobos and Deimos.* Acta Astronautica Vol. 45, Nos. 4-9, pp. 301-309.

Rivkin, A. S., Brown, R. H., Trilling, D. E., Bell III, J. F. and Plassmann, J. H. 2001. *Near-Infrared Spectrophotometry of Phobos and Deimos.* Icarus 156, pp. 64-75.

Sagdeev, R. Z., Balebanov, V. M., Zakharov, A. V., Kovtunenko, J. M., Kremnev, R. S., Ksanfomality, L. V. and Rogovsky, G. N. 1987. *The Phobos Mission: Scientific Goals.* Adv. Space Res. Vol. 7, No. 12, pp. 185-200.

Shkuratov, Yu., Opanasenko, N., Basilevsky, A., Zhukov, B., Kreslavshy, M. and Murchie, S. 1990. *A Possible Interpretation of Bright Features on the Surface of Phobos.* Planet. Space Sci., Vol. 39, No. 1/2, pp. 341-347, 1991.

Simonelli, D. P., Wisz, M., Switala, A., Adinolfi, D., Veverka, J., Thomas, P. C. and Helfenstein, Paul. 1997. *Photometric Properties of Phobos Surface Materials From Viking Images.* Icarus 131, pp. 52-77.

Singer, F. S. 1999. *The Ph-D Proposal: A Manned Mission to Phobos and Deimos.* Website: www.sepp.org/Ph-Dproject Accessed 01/05/2006.

Stooke, P. J. 2000. *Stratigraphy of Phobos.* Lunar and Planetary Science.

Szeto, A. M. K. 1983. *Orbital Evolution and Origin of the Martian Satellites.* Icarus 55, pp. 133-168.

Thomas, P. and Veverka, J. 1980a. *Crater Densities on the Satellites of Mars.* Icarus 41, 365-380 (1980).

Thomas, P. and Veverka, J. 1980b. *Downslope Movement of Material on Deimos.* Icarus 42, pp. 234-250.

Thomas, P. C., Adinolfi, D., Helfenstein, P., Simonelli, D. and Veverka, J. 1996. *The Surface of Deimos: Contribution of Materials and Processes to Its Unique Appearance.* Icarus 123, pp. 536-556.

Walker, R. J., Ball, A. J., Price, M. E., Sims, M. R., Taylor, F. W., Wells, N. S. and Zarnecki, J. C. 2005. *Concepts for a low-cost Mars micro mission.* Acta Astronautica.

West, M. 2006. *Personal Correspondence*. Research School of Physical Sciences and Engineering, The Australian National University, Canberra.

Yoder, C. F. 1981. *Tidal Rigidity of Phobos.* Icarus 49, pp. 327-346.