Introduction to JAXA's Exploration of the Two Moons of Mars, with Sample Return from Phobos

26 October, 2015

Phobos/Deimos Sample Return Mission Study Team

Document distributed prior to the international review on 2 November, 2015.

<Science Goals>

Mars is the outermost planet among the rocky planets in the solar system. Phobos and Deimos are the two moons of Mars. JAXA's Martian moons mission will make close-up remote sensing and in-situ observations of both moons, and return samples from Phobos.

With this mission, we will give a boost to planetary science by adding new information on planetary formation and evolution processes in the part of the solar system linking its inner- and outer-part. The origin of Phobos and Deimos itself is a nice question to answer, but revealing the origin will enable us to step further forward to constrain the behavior of small bodies in the close proximity to the border between the inner- and the outer-part of the solar system in its making. Small bodies in the internal boundary part of the early solar system are considered to have played a key role in providing habitability to the rocky planets. Focusing on the moons will also provide a vantage point from which new insight on how the Mars system, including its surface environment, evolved in time.

There are two leading ideas for the origin of the two moons: captured asteroid or giant impact. While not a small amount of remote sensing data exist for Phobos, not enough has been gained to judge between the two ideas for its origin. It is likely that remote sensing data alone would not lead us to a definitive conclusion. Returning of samples which represent the original building blocks for detailed analysis to be performed on the ground is the way to give the end to the debate that would otherwise last forever. That is, a sample return mission to Phobos is what should be done to reveal its origin and to make substantial steps beyond. Our goal is to enhance our understanding of planetary formation processes at the outer-edge of the rocky planet region in our solar system.

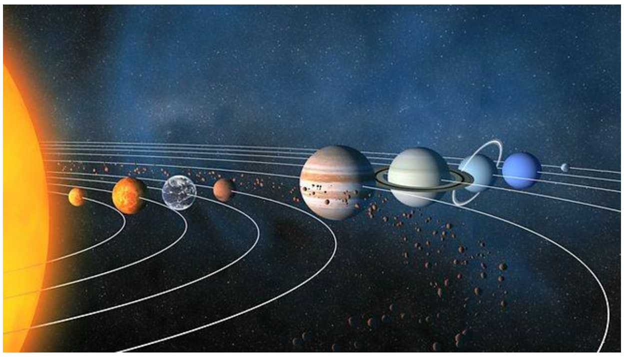

Figure: Mars sits at the outer-edge of the rocky planet region.

A sample return mission requires more time and faces more technical challenges and risks. Yet, the merit brought-in due to outstandingly superior analytical capability provided by ground facilities, especially compared to the quality of data expected from instruments onboard a spacecraft, overrides the unfavorable aspects of a sample return mission. Indeed remote sensing data becomes more valuable when credibility in their interpretation is supported by sample analysis results.

Sample return from Phobos would enable us to reveal its origin. Close-up observations of Deimos, and that with reference to the ground-truth results from Phobos, would enable us to give strong constraint to the idea for its origin. That is, the mission aims to deploy an integrated study on the origin of the two moons and to open a new window for our understanding of the formation processes in this critical part of the solar system. If the origin of Phobos is known to be captured primordial asteroid (D-type as has been inferred from visible-wavelength and (very limited) near-IR spectroscopic remote sensing data), detailed analysis of the samples allows us to study how the primordial materials, namely, water and organic compounds, are brought into the inner-part of the solar system from the outer-part across the border (the snow line). Sample analysis also allows us to unveil the migration history of the small body that behaved as a capsule which carried water and organic compounds into the inner-solar system. These studies will constrain the initial condition of the Mars surface environment and of rocky planets in the solar system. If the origin of Phobos turns out to be giant impact, samples will be composed of ancient Mars and impactor materials. In a sense, Mars sample return is realized. Their analysis will reveal the impact size and allow us to evaluate how the initial evolution of Mars surface environment was affected by the violent satellite formation process.

Due to its close orbit to Mars, Phobos would have been showered by debris generated by impact events on the surface of Mars. That is, we may find samples from ancient Mars surface among samples to be collected from Phobos (even if its origin does not turn out to be giant impact). The Mars samples may span over a wide range in time and may enable us to read-out the evolution history of Mars surface environment. The orbit of the Martian moons mission also provides an interesting vantage point allowing global perspective to inspect how water in the present Mars ground-air system is cycled, which would be a critical element in the Mars climate system and its evolution. The mission orbit also provides occasions to make in-situ observations of particles to learn about atmospheric escape mechanisms of the present Mars, which helps us develop our idea for the huge loss of the atmosphere that happened in the past. That is, the mission is not only about the moons but also is our first approach to Mars itself, with the scientific focus on its surface environment transition.

<Engineering aspect of the mission>

As symbolically indicated by the success of the Hayabusa mission that returned samples from Asteroid Itokawa, it is the style of Institute of Space and Astronautical Science (ISAS, JAXA) that engineering and science departments work together to make a cutting-edge space science mission happen. This was true for the development of Hayabusa2 and applies to this Martian moons mission as well. The opportunities offered by this mission to space engineering are: trajectory control to arrive at Mars moons, landing and sampling on the surface of Phobos, return trip from Mars to Earth and upgrading the deep-space communication technology.

Figure: Hayabusa2, launched in December 2014, to the C-type asteroid of Ryugu, will return samples to Earth in 2020.

<Science background>
Here the background leading to the science goals of this Martian moons mission is described.

In a document issued in February 2015, Japanese planetary science community expressed its interest in setting the theme of pre-biotic environmental evolution as the commonly shared grand theme to be pursued by the community members. In addition to the intrinsic attraction that the theme has, success of Hayabusa and the fact that Hayabusa2 is ongoing are the drivers behind this statement. ISAS has completed an asteroid sample return mission and is running another one to a primordial asteroid (the C-type asteroid of Ryugu) from which more hints are expected to be gained on the origin of water and organic compounds brought to the habitable zone of the solar system (including, of course, Earth). That is, Japanese community is at a stand point where it can make a strong contribution to the pre-biotic environment evolution theme from an interesting angle.

This Martian moons mission is aligned with the idea to return samples from small bodies to learn more on the making of the solar system. The transition of the Mars environment has been and is one of the focal points in the world-wide planetary science. There has been and will be huge resources invested into this topic. Orbiters making high-resolution remote sensing of the planet and rovers exploring its surface are revealing the dramatic transition that the Mars surface environment went through. There has been no successful ISAS mission to Mars, however, the interest in the Japanese community has been naturally always strong. While it may take some more time before ISAS is ready to send a rover to the surface of Mars, this Martian moons mission will enable us to approach the same grand theme from a different angle in a carefully fabricated way.

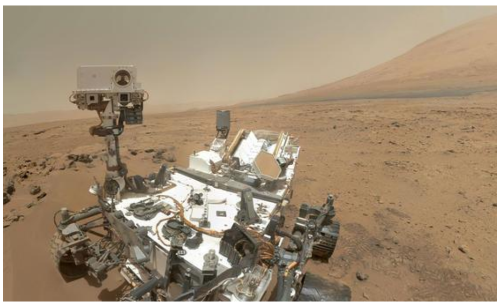

Figure: The Martian moons mission will enable us to approach the same grand theme as the one pursued by the rovers on Mars.

Beautiful synergy between remote sensing from orbiters and geological/geochemical exploration by landers/rovers has revealed what Mars used to be 3.5 billion years ago: Huge amount of water must have been present on the surface of the planet. In contrast, more than 3.8 billion years ago, some evidence exists to show that water amount on the Mars surface was limited and instead large-scale hydro-thermal processes were taking place in the sub-surface world. Little is known on the yet older times when Mars was in its initial evolution stage. It is also important to understand how water was brought to the planet, that is, the process that set the initial condition. Mars is the outermost rocky planet and sits at the gateway position to the outer-part of the solar system. In addition to the interest in the Mars history itself, understanding the water delivery to the planet located at the outer-boundary of the rocky planet region is very important for our understanding of the initializing process of the habitable zone in our solar system.

ISAS's way to approach the attractive target of Mars is to focus on its initial evolution and investigate it from the viewpoint of <How was the primordial material delivered to the planet?> When one looks at Phobos and Deimos from this perspective, the question of their origin becomes upgraded. That is, once we understand their origin, we would know what information related to the initial evolution of Mars that the moons retain. Sample return from Phobos and/or Deimos is the way to read-out the retained information. Hayabusa2, a sample return mission to the C-type asteroid Ryugu, will conclude if primordial asteroids were the reservoirs of pre-biotic organic compounds and water that were transported to Earth. We may locate this Phobos sample return mission along the same line in the planetary exploration roadmap: Phobos may turn out to be the direct evidence for the delivery process taking place across the border (the snow line) between the inner- and the outer-solar system. This Martian moons mission with the overarching goal would be a compelling way for ISAS to make its first step into the world of Mars exploration.

Sample return from Phobos is needed to conclude definitely its origin that is being debated. Sample return is needed to step beyond simply pinning-down the origin and to reveal the formation processes (either capturing of a water-delivery capsule or giant impact on the ancient Mars) that had substantial impact on the initial evolution of Mars. Sample return from Phobos does not necessarily require too large resources and is one of the best mission ideas by which ISAS's expertise in sample return from small bodies is rewarded most.

The February 2015 document issued by Japanese planetary scientists lists five paths to reach the grand theme of pre-biotic environment evolution. Among the five, the Martian moons mission contributes to the grand theme via the following four paths:

(A) Prebiotic synthesis and evolution of building blocks of life in the early solar system

(B) Migration and delivery of building blocks of planets and life in the solar system

(C) Initial evolution and differentiation of planets and satellites

(D) Surface environment evolution under energy input from the Sun

(A) becomes available when the origin of Phobos is known to be captured primordial asteroid. (D) is available because remote sensing observations of Mars itself will be performed from the unique global vantage point in the proximity of the moons. The fact that (D) also applies to this mission indicates that the Martian moons mission also enables Mars science to be deployed from the data it will acquire.

<Mission scenario>

The JAXA's Martian moons mission has two science goals:

<Goal 1> To reveal the origin of the Mars moons, and then to make a progress in our understanding of planetary system formation and of primordial material transport around the border between the inner- and the outer-part of the early solar system.

<Goal 2> To observe processes that have impact on the evolution of the Mars system from the new vantage point and to advance our understanding of Mars surface environment transition.

Each mission goal has science objectives as follows:

<Goal 1>

1.1 To determine whether the origin of Phobos is captured asteroid or giant impact.

1.2a (In the case of captured asteroid origin) To understand the primordial material delivery process (composition, migiration history, etc.) to the rocky planet region and to constrain the initial condition of the Mars surface environment evolution.

1.2b (In the case of giant impact origin) To understand the satellite formation via giant impact and to evaluate the how the initial evolution of the Mars environment was affected by the moon forming event

1.3 To constrain the origin of Deimos

<Goal 2>

2.1 To obtain a basic picture of surface processes of the airless small body on the orbit around Mars

2.2 To gain new insight on Mars surface environment evolution

2.3 To better understand behavior of the Mars air-ground system and the water cycle dynamics

In order to show how these objectives are achieved, the mission scenario is described here.

(1) Mars orbit insertion
(2) Transfer to a quasi-satellite orbit around Phobos for close-up observations
(3) Landing and sampling from Phobos
(4) Transfer to Deimos for multi-flyby observations (or from a quasi-satellite orbit).

(5) In-situ space observations and Mars remote sensing observations for Mars atmospheric science themes while the spacecraft is within the Mars gravitational sphere.
(6) Departure from Mars and return to Earth
(7) Recovery of samples and initial analysis

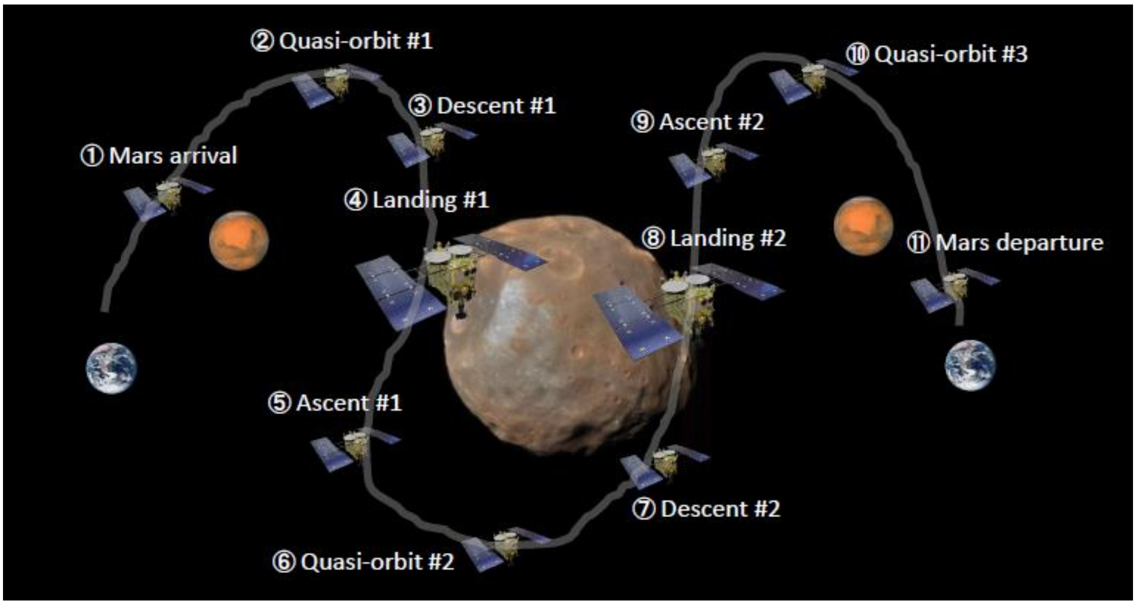

Figure: Mission profile.

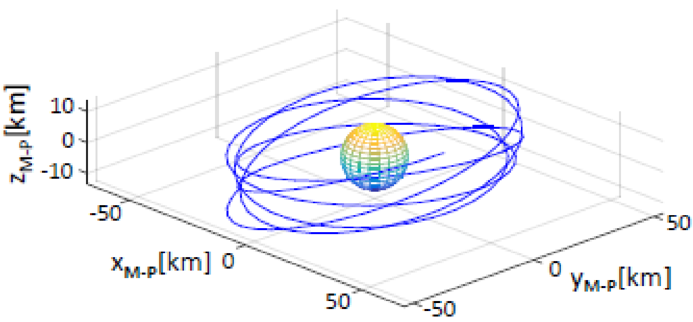

Figure: A quasi-satellite orbit around Phobos.

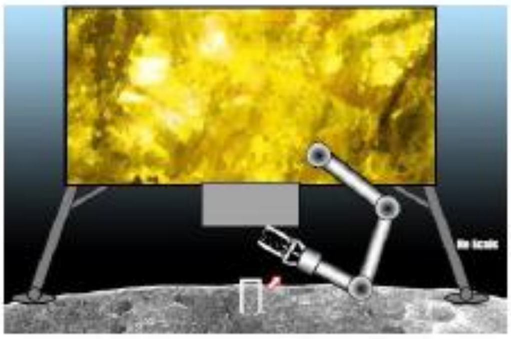

Figure: Landing and sampling.

In Phase (2), remote sensing observations will characterize the surface of Phobos and enable us to select the landing site(s) from where samples are collected. In order to resolve the origin enigma, samples should contain original building blocks of Phobos while some part of its surface may be covered by materials of external origin that were attached to the surface later in the Phobos history. Spectroscopic mapping will enable us to avoid the area which is covered heavily by materials of external origin and to select the right spot where genesis samples can be collected. Spectroscopic observations alone, however, will not be able to completely determine the origin of Phobos because of the obstacles set by space weathering. In this sense, spectroscopy of not only space-weathered regolith but of a fresh surface of a boulder, which will be tried in the mission, may make a breakthrough. The space weathering effects can be easily separated during sample analysis on the ground and is not regarded as an obstacle at this stage of the mission. Another role of remote sensing is to record the sampling site information that is to be coupled to sample analysis studies. Thermal inertia is the property that is tightly coupled to the regolith particle size and can be constrained by remote sensing observations as well. It is nice to have a nice inference of the regolith particle size prior sampling operations.

In-situ observations performed during Phase (2) are, (a) search for water-related ions originating from H_2O outgassing from possible water-ice inside Phobos, (b) search for large-scale high-mass density contrast inside Phobos and (c) elemental composition measurements. Both (a) and (b) are targeted at indirect detection of possible ice inside the moon. If positive, it gives a strong support to the idea that Phobos is a captured asteroid. (c) is designed so that the obtained data will tell the mixing ratio between the chondritic component and the differentiated Mars material. In an extreme case, the Phobos origin may be well constrained by the data.

In Phase (3), the spacecraft will land on the surface for ~1 hour and collect samples. The sample amount is 10g as requested by the analysis plan that is set so that the objectives of the mission will be achieved. Not only the Phobos genesis samples but also debris from the ancient Mars are expected to be included in those collected from the regolith.

In Phase (4), remote sensing of Deimos will be performed to obtain spectroscopic mapping of regions of interest. Limitations would apply due to the nature of the spacecraft orbit, but elemental composition measurements will be tried during the Phase (4) as well. Information gathered by these observations, with assist from knowledge and insight gained at Phobos, will enable us to constrain the origin of Deimos.

In Phase (5), in-situ observations of Mars atmospheric ions are made to constrain the atmospheric escape mechanism. Remote sensing of Mars will be made so that global monitoring of water-cycle and dust interaction in the Mars air-ground system will be available. The new global perspective would add key information for a better understanding of the climate system.

In Phase (7), various analysis scheme will be applied to judge the origin of Phobos, to decipher the whichever major event in the early history of Mars and, if found, to inspect ancient Mars samples that keep the records of what the surface environment used to be. Experience with Hayabusa and Hayabusa2 missions sets the basis for the sample analysis plan.

<Missions to Phobos and Deimos>

Most of the observations of the Martian moons have been made by spacecraft whose main objectives were to explore the Mars, with the largest contribution coming from ESA MarsExpress. MarsExpress continues to obtain color images of Phobos in its extended mission phase.

Multiple near-flybys in the past have constrained the volume and the mass of each moon at 10% accuracy. The average density is, 1.85g/cm^3 for Phobos and 1.48g/m^3 for Deimos, respectively. The orbits of the moons are well known, with Phobos located at inside of the corotation radius drifting inward towards Mars and with Deimos at outside of the corotation radius moving outward from the planet. Imagery data show that both have irregular shapes, with their surfaces covered by thick regolith layers and many craters. Phobos is known to have the red terrain and the blue terrain. The red terrain of Phobos is similar to what the surface of Deimos looks to be.

Phobos has ~1300 craters that have diameters larger than 200m, implying an old surface (3.7~4.3 Ga). The typical size of blocks is 15-30m, with the maximum size at ~100m. It should be noted that most of the largest blocks are identified in a limited set of high-resolution (a few meters) images. The size distribution from Phobos may look similar to those obtained from asteroids (Eros and Itokawa), but since the whole surface is not covered by images of uniform spatial resolution, it is not conclusive. Blocks are seen on Deimos as well but the low resolution data do not allow us a statistical study. It would be interesting to note that the largest size on Deimos is 150-200m and thus is larger than the one on Phobos. While both Phobos and asteroids are small airless bodies, it is possible that its residence in the Mars environment would have modified the surface properties seen at Phobos from those seen at asteroids in the interplanetary space. The largest difference between the two situations is that, in an orbit around Mars, debris from the surface of a small body is likely to re-accrete and form a thicker regolith.

Both Phobos and Deimos show low reflectance and monotonic spectrum shapes, in resemblance with a D-type asteroid. Meanwhile, near-IR spectroscopic observations are very limited (only from a few spots, and that with low spatial resolution) and surface material mixing due to lateral mobility could have blurred possible spectroscopic features. Most importantly, there is lack of observations at the two key wavelengths, 0.65 and 2.8 micron.

Information of the internal structure is very limited. A shape model of Phobos is constructed with 12m/pixel resolution while that for Deimos has an order of magnitude worse resolution and the volume (average mass density) is not well-constrained. From the data showing the amplitude of forced-libration, it has been proposed that there is no significant mass density heterogeneity inside Phobos.

The figures below show the image data coverage by HRSC onboard MarsExpress of Phobos and Deimos, respectively. The color indicates the spatial reolution. Regarding Deimos, good coverage is limited to the sub-Mars hemisphere.

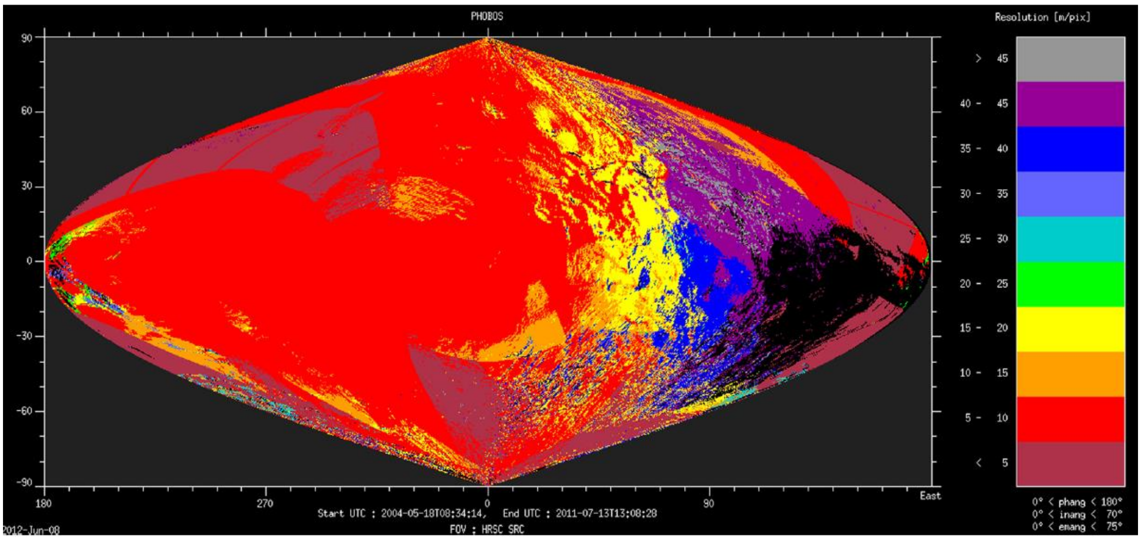

Figure: MarsExpress imaging coverage at Phobos.

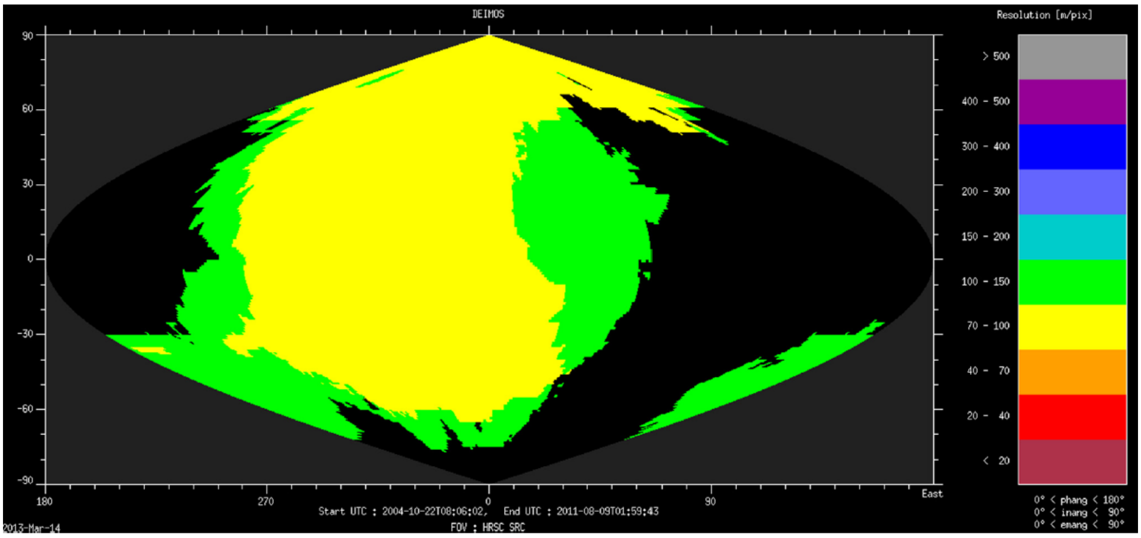

Figure: MarsExpress imaging coverage at Deimos.

A Russian mission Phobos-Grunt that had aimed at returning samples from Phobos failed because of a launch problem. Three proposals had been submitted to NASA's call for Discovery mission but none of them were selected in 2015. There is no solidly defined mission to Phobos and/or Deimos at this moment.

<Enigmatic origin of Phobos and Deimos>

The two leading ideas for the origin of the Martian moons are captured asteroid and giant impact. The former requires the orbital energy of the asteroid to be dissipated within the Mars gravitational sphere. The latter assumes that a moon was accreted from a debris disk around Mars that had been formed upon impact on the planet. At present, there is no consensus regarding the result of the contest between the two ideas, nor neither can satisfy all the constraints given from existing data.

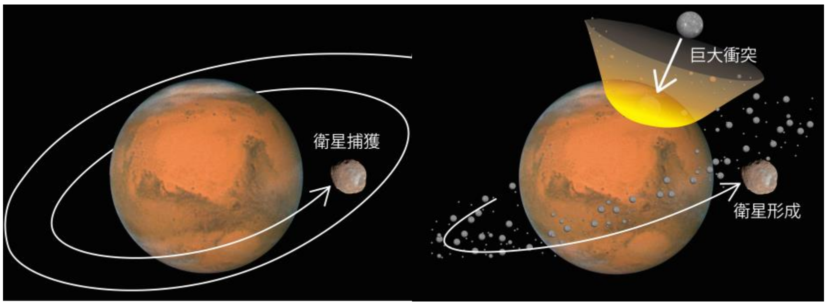

Figure: Captured asteroid (left) or giant impact (right)?

Characteristics of the moons related to the origin theme are:

(1) The masses of Phobos and Deimos (1.06 x 10^{16}kg and 1.51x10^{15}kg, respectively) are both by far smaller than the mass of Mars (6.42x10^{23}kg)

(2) Both orbits are mostly circular (eccentricity e=0.01511 and 0.00024, respectively) and mostly on the Mars equatorial plane (Inclination I=1.08 and 1.79 deg, respectively).

(3) Phobos is inside and Deimos is outside the corotation radius, respectively.

(4) The average mass densities are lower than the typical value for rocks (1.85g/cm^3 and 1.48g/cm^3, respectively, compared to 2.5-3g/cm^3). This fact implies either presence of ice or large porosity inside the bodies.

(5) Spectroscopic observation results resemble those from D-type asteroids.

Irregular satellites in the Jovian system (with large e and nonzero I) are understood to be captured small bodies. The idea of captured primordial asteroid for the origin of Phobos and Deimos is supported by the observed spectroscopic characteristics and is consistent with the low mass density which may suggest the presence of ice. The capture process requires the orbital energy of the asteroid to be dissipated. Candidate dissipation processes are (a) tidal interaction with the planet, (b) three-body interaction and (c) gas drag. (a) and (b) are considered to result in an orbit with high e and I with a large semi-major axis. Reduction of these orbital parameters down to the present value of Phobos is not impossible but with difficulty associated especially with *I*. For Deimos, there is no proposed mechanism for the reduction. For (c), because the orbital evolution time scale is short, the gas effect, from either the proto-solar disk gas or the primordial Mars atmosphere, needs to disappear in a very timely manner (for example, the disk gas disappearing quickly upon arrival of the asteroid to the Phobos orbit). There is generic difficulty in reducing *I*.

The difficulty with *I* that spans all the processes (a) - (c) can be avoided by assuming that the asteroid entered with low *I* initially. The probability of having two asteroids (one to become Phobos and the other to become Deimos, respectively) entering initially with low *I*, however, is very small (10^{-7}).

The Earth's moon is considered to be created by giant impact. There is an idea that Martian moons are formed by the same process. At Mars, the satellite-to-planet mass ratio (2×10^{-8}) is much smaller than at Earth (0.01). A much smaller impactor can be responsible for the possible Mars event. The smaller impact event may have left a mark (a crater) on the Mars surface that may be still preserved today. The impact event creates a debris disk on the Mars equatorial plane and naturally explains the low *I* of Phobos and Deimos. Shock heating upon impact results in such a high temperature as to cause most of the impact-generated debris to be melted. Once melted debris cool down quickly to form a debris disk around Mars. The moons accreted within the debris disk are of porous body nature which is consistent with the observed low-density property of Phobos and Deimos. Borealis basin (a crater of 7700km diameter) located in the northern hemisphere of Mars is discussed to be the trace of the impact event that created Phobos and Deimos. From the crater size the mass of the impactor is estimated to be 2.6% of the Mars mass. The moons formed in this way are mixtures of materials from Mars and from the impactor. The mixing ratio, although not studied quantitatively in detail, is inferred to be half-and-half by analogy to what we know from Earth and the Moon case.

A numerical simulation study shows that, from a compact debris disk whose outer-edge was at the corotation radius, many moon-like bodies formed and the outermost one had the mass similar to that of Phobos. The location of this Phobos-like body, however, was not close enough to the corotation radius that it fell quickly into the Mars within 200M years. The compact disk does not give birth to a Deimos-like moon that is located outside the corotation radius.

In another simulation that assumes a 2.6% Mars mass impactor, the debris disk evolution was followed and it was found to result in moons much larger than Phobos or Deimos. Study on cases with smaller impactors remains undone.

From samples to be obtained by the Martian moons mission, if the origin is found out to be captured asteroid, the target themes will be water delivery to rocky planets and primordial material evolution within small bodies around the slow line of the early solar system. The keywords for Phobos sample analysis will be volatiles, hydrated minerals and organic compounds. D/H ratio and C/N – C/O ratios are good indicators to tell the environment that the asteroid used to be in before the capture by Mars. Here, good synergy with Hayabusa2 and OSIRIS-REx is expected. Ar-Ar chronology applied to a regolith particle would tell its impact history. Successful application of the technique to Itokawa samples returned by Hayabusa has been reported. Obtaining a histogram of the impact ages for ~100 particles may tell the age of the Stickney crater, the largest crater on Phobos: Debris from the largest crater forming event, while retaining the information of the original building block of Phobos, are expected to re-accrete and constitute a major component of regolith population if the impact took place when Phobos was already in an orbit around Mars.

If the origin turns out to be giant impact, the target science will be to decipher the impact process, that is, to read-out the size of the impact event and to know where the impactor came from, to infer how much influence the moon forming event had on the initial evolution of the Mars surface environment and to better understand the satellite formation process in the rocky planet region of the solar system. Top priority in the sample analysis will be on obtaining the mixing ratio between Mars material and impactor material. The highest temperature experienced by the samples is also among the key information to tell the size of the impact. Volatile content is among important information to be obtained from the sample analysis. Ar-Ar chronoloGapplied to each regolith particle would produce an age distribution data. It is expected that there will appear a feature in its histogram that would tell the age of the impact event: Was it 4.5 Ga as the Earth’s moon forming event is known to be, or was it 3.9 Ga during the late heavy bombardment phase?

It is repeated that knowing the origin of Phobos is not our goal. Knowing the origin and with Phobos samples in our hand, the research horizon opens to reveal the dynamics of the inner-outer linkage region of the early solar system.

<Trade-off consideration: Is sample return necessary?>
Sample analysis will very likely reveal the origin of Phobos. Then the question here is in what case, in any, remote sensing and in-situ observations will firmly reveal the origin.

An idealistic case is when the followings are all met: (a) Spectroscopic mapping shows that hydrated minerals are wide-spread over the body. (b) Ion observations and gravity measurements indicate the presence of ice inside the body. (c) Elemental composition measurements show dominance of the chondritic components. In this case, the Phobos origin is very likely to be captured primordial asteroid. On the other hand, if the origin is giant impact, only non-definite negative detection of (a) and (b) combined with (c') Elemental composition measurements showing the dominance of Mars material, would be the output from the observations. That is, since the negative detections do not compose a strong argument, (c') alone would be the only supporting evidence, which is not a very convincing situation.

With samples returned to Earth, we can take time to make ourselves ready for unexpected findings. There are two leading ideas for the origin of the moons but the data from the spacecraft may show a hint of something else. Science exploration into the new direction that is undefined until the moment of the discovery is doable when samples are at hand. Unlike spacecraft operation, there is plenty of time for re-designing an analysis plan after making an initial inspection of samples.

What is most important, our goal is not simply to understand the origin of the moon but to step ahead to learn more on the solar system formation in this inner-outer linkage region of the solar system. This next step is possible only with sample analysis.

Figure: Extra-terrestrial Sample Curation Center at ISAS.

It should be noted at the same time that we will not obtain samples from all over the surface of the body but only from a very limited number of spots. In order to know clearly what the samples represent about the moon, the importance of remote sensing cannot be over-stressed. Global characterization of the surface will tell where the sampling sites stand in the global map. Local properties of sampling sites need to be characterized over a meso-scale (~100m) area in addition to recording of sampling operation that that would focus on a ~1m area around the sampling spot. The multi-scale remote sensing coverage with zooming centers at the sampling sites is indispensable to maximize the science output from sample analysis.

<Trade-off consideration: Phobos or Deimos?>

Resource limitation does not allow sample return from both moons. Phobos is selected as the result of the trade-off consideration as follows:

- The origin of Deimos is more puzzling.
- Phobos has two terrains, red and blue, with the red terrain considered to be more space-weathered.
- Existing data (images, shape model, etc.) of Phobos enable better planning for the sampling operation.
- Deimos surface is considered to be similar to the red terrain of Phobos,
- Debris from Mars are expected to be included in the Phobos regolith samples but are unlikely to be above a detection limit from Deimos.

It was judged that Phobos samples are more valuable because (1) there is a chance that good inference of Deimos materials can be made by analyzing Phobos samples and (2) expectation of Mars samples to be returned from Phobos.

Figure: Phobos (right) and Deimos (left).

<Mission requirements>

The science objectives are broken down at a sub-layer and each item at the layer has a mission requirement (MR) associated with it.

<Goal 1> To reveal the origin of the Mars moons, and then to make a progress in our understanding of planetary system formation and of primordial material transport around the border between the inner- and the outer-part of the early solar system.

<Science Objective 1.1> To determine whether the origin of Phobos is captured asteroid or giant impact.

[1.1.1] To characterize the materials that constitute Phobos via spectroscopy in order to evaluate a sampling site candidate from the view point of Science Objective 1.1.

MR1.1.1: Sepctroscopic mapping of major regions of Phobos at 20m spatial resolution, with emphasis on hydrated mineral features, and with intention to select an appropriate sampling site. The same mapping but at 1m resolution of the area within 50m from a selected sampling spot. Measurement of globally-averaged elemental abundance ratios of Ca/Fe and Si/Fe.

[1.1.2]: To identify genesis samples among those collected from Phobos and to perform sample analysis in order to constrain the origin of Phobos.

MR1.1.2: Acquisition of more than 10g samples from deeper than 2cm below the surface after selecting carefully the sampling site that meets Science Objective 1.1. Analyze the samples by texture inspection and by mineralogical/elemental/isotopic composition measurements at the precision that meets Science Objective 1.1.

[1.1.3]: To obtain indirect information on the Phobos internal structure in order to constrain the origin of Phobos independent of the sample analysis results.

MR1.1.3: With special attention to possible presence of water-ice inside Phobos, (1) Measurement of ions related to possible outgassing from the internal ice, at the detection limit corresponding to the outgassing rate of 10^{22} /sec or lower. (2) Search for signatures indicating the presence of ice concentration whose mass is more than 10% of the Phobos mass, (3) Search for signatures indicating substantial mass density heterogeneity near the surface.

<Science Objective 1.2a> (In the case of captured asteroid origin) To understand the primordial material delivery process (composition, small body

migration process, etc.) to the rocky planets of the solar system and to constrain the initial condition of the Mars surface environment evolution.

[1.2a.1]: To design and perform an analysis plan that extracts information pointing to small body evolution around the slow line in the early solar system and to the capture process of Phobos by Mars.

MR1.2a: Analyze the samples by texture inspection, by elemental/isotopic composition measurements and by formation age dating, at the precision that meets Science Objective 1.2a. Analyze hydrated minerals and organic compounds. Obtain statistical distribution of impact ages of samples and perform crater chronology in order to read-out the collisional history of Phobos.

<Science Objective 1.2b> (In the case of giant impact origin) To understand the satellite formation via giant impact and to evaluate the how the initial evolution of the Mars environment was affected by the moon forming event.

[1.2b.1]: To design and perform an analysis plan that extracts information pointing to the giant impact that formed Phobos and to the nature of the impactor.

MR1.2b: Analyze the samples by texture inspection, by elemental/isotopic composition measurements and by metamorphic age dating, at the precision that meets Science Objective 1.2b. Obtain the highest temperature that the samples experienced during the impact. Obtain the mixing ratio between the Mars differentiated material and the impactor material.

<Science Objective 1.3> To constrain the origin of Deimos.

[1.3.1]: To characterize the materials which constitute Deimos via spectroscopy, in order to compare the results with those from Phobos.

MR1.3: Spectroscopic mapping of major regions of Deimos at 100m spatial resolution, with emphasis on hydrated mineral features.

<Goal 2> To observe processes that have impact on the evolution of the Mars system from the new vantage point and to advance our understanding of Mars surface environment transition.

<Science Objective 2.1> To obtain a basic picture of surface processes of the airless small body on the orbit around Mars.

[2.1.1]: To characterize the space environment and the surface features of

Phobos, with the intention of comparison with asteroids.

MR2.1: Monitor the space environment around Phobos. Image surface features (craters, blocks, sedimentary feature in regolith layers, etc.) at 20m resolution. Study space weathering processes via sample analysis.

<Science Objective 2.2> To gain new insight on Mars surface environment evolution.

[2.2.1]: To identify Mars samples among those collected from Phobos and to perform sample analysis in order to learn the environment evolution of the Mars surface.

MR2.2.1: Search for Mars samples. When detected, analyze the samples by elemental/isotopic composition measurements and by impact age dating. Measure remnant magnetization of samples.

[2.2.2]: To understand the mechanism of atmospheric escape from the present Mars in order to constrain the huge atmospheric loss process in the past.

MR2.2.2: Measurements of isotopic ratios of major ion species (O^+, C^+, N^+, Ar^+) escaping from Mars with 50% precision.

<Science Objective 2.3> To understand better the behavior of the Mars air-ground system and the water cycle dynamics.

[2.3.1]: To obtain a global picture of dust and water vapor spatial distribution and its temporal variation.

MR2.3: Continuously observe global characteristics of dust storms, ice clouds and water vapor spatial patterns at mid-latitudes with an image cadence shorter than one hour.

<Model payload>

Among the ten Mission Requirements, four (MR1.1.2, 1.2a, 1.2b, 2.2.1) are related to sample analysis. The first one (MR1.1.2) sets requirements for the sampling scheme. Three (MR1.1.1, 1.1.3, 2.1) out of the remaining six issue requirements for remote sensing and in-situ observation instruments onboard the spacecraft. The remaining three (MR1.3 (Deimos), 2.2.2 (Mars in-situ), 2.3 (Mars remote sensing)) do not necessarily need new instruments but only issue requirements for science operation.

A list of model payloads that would fulfill the mission requirements is as follows:

[sample science]

- Sampler: Acquisition of more than 10g Phobos genesis samples

[remote sensing]

- Visible camera: To image geologic features
- Near-IR spectrometer: For spectroscopy of mineralogical signatures and for Mars atmospheric observations
- Mid-IR radiometer: To obtain thermal properties of the surface and for Mars atmospheric observations

[in-situ observations]

- Gamma-ray/neutron spectrometer: For elemental composition measurements
- Ion mass spectrometer: To detect degassing from possible ice inside Phobos, for Phobos space environment theme and for Mars atmospheric escape theme
- Gravity gradiometer: To detect mass density heterogeneity inside Phobos
- Dust counter: For Phobos space environment theme

<Success criteria>

The success criteria of the mission are set as follows:

<Minimum success criteria>

Pertaining to remote sensing observations,

(1) Perform imaging and spectroscopic observations of the major regions of Phobos with unprecedented spatial resolution (Science Objective 1.1).

(2) Perform high resolution imaging of the regions of interest on the surface of Phobos to constrain surface weathering and metamorphic processes (Science Objective 2.1).

<Full success criteria>

Pertaining to Phobos observations,

(1) Geological and spectroscopic mapping of a substabtial fraction of the Phobos surface (Science Objective 1.1).

(2) Identify locations that bear original building blocks of Phobos (Science Objective 1.1).

(3) Set an upper limit to the outgassing rate from possible ice inside Phobos (Science Objective 1.1).

Pertaining to sample analysis,

(I) Sample acquisition from a site on Phobos and identification of Phobos genesis samples among those that are returned (Science Objective 1.1).

(II) Complete a sample analysis menu for a primordial asteroid including chronology, or Differentiate Mars material from impactor material and perform impact age dating (Science Objective 1.2a/b).

(III) Analyze space weathering process (Science Objective 2.1).

(IV) Search for debris from Mars in samples returned from Phobos. Set an upper limit for its detection probability upon non-detection (Science Objective 2.2).

Pertaining to Deimos observations,

- Produce geological and spectroscopic mapping of characteristic region of Deimos to be compared with the map for Phobos (Science Objective 1.3).

Pertaining to Mars atmospheric science,

(a) Measure the isotopic ratio of major ions escaping from Mars (Science Objective

2.2).

(b) Reveal the temporal evolution of dust storms, ice cloud and water vapor spatial pattern (Science Objective 2.3).

<Extra success criteria>

Pertaining to Phobos science,

(1) Analysis of samples returned from more than one spot on Phobos having different geological characteristics. Anchoring of remote sensing maps to ground truth results obtained from sample analysis (Science Objective 1.1).

(2) Positive detection of signatures of ice inside Phobos (Science Objective 1.1).

(3) Deciphering migration of small bodies and their influence on the initial evolution of Mars surface environment from the primordial material samples returned, or Constrain the size and the date of the giant impact event (Science Objective 1.2a/b).

(4) Understand the surface processes of Phobos embedded in the Mars system, as compared with those at asteroids (Science Objective 2.1).

Pertaining to Deimos science,

- Constrain the origin of Deimos by also referring to the results from Phobos data and sample analysis (Science Objective 1.3).

Pertaining to Mars science,

(a) When abundant Mars samples are found, perform sample analysis to constrain the history of Mars surface environment evolution (Science Objective 2.2).

(b) Estimate the total amount of atmosphere lost from Mars in its history (Science Objective 2.2).

(c) Reveal the behavior of dust and water in the Mars air-ground system at one hour time resolution, and its seasonal dependence. (Science Objective 2.3).