**Martian Moons eXploration (MMX)**

*Japanese next-generation sample return mission*

- JAXA officially approved MMX in Feb. 2020 (now in Phase B)
- Launch in **2024**
- Phobos: remote sensing & *in situ* observation
- Deimos: remote sensing observation (multi-flyby)
- Retrieve **samples (>10 g) from Phobos** & return to Earth in **2029**

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**THE 1ST SAMPLE RETURN MISSION FROM THE MARTIAN SATELLITES!**
WHY PHOBOS AND DEIMOS?

Regolith of Phobos/Deimos contains Martian building blocks, impactors, late accreted volatiles, ancient Martian surface components etc...

• Constrain the initial condition of the Mars-moon system
• Gain vital insight and information on the source(s) and delivery process of water (& organics) into Mars and the inner rocky planets
MMX Science Goals

<Goal 1>
To **reveal the origin of the Martian 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 impacts on the evolution of the Mars system** from the new vantage point and to advance our understanding of Mars surface environment transition

**Capture of asteroid**
Consistent with D- or T-type IR spectra

**in situ formation by an impact**
Consistent with low eccentricity & inclination

Image courtesy (Hiro Kurakawa)
Mission Profile

- The total of 5 years trip by use of chemical propulsion system
- Interplanetary flight: 1 year for outward/homeward
- Stay at curcum-Mars orbits 3 years

Launch in 2024
- Phobos: landing
- Deimos: multi-flyby
- Return to Earth in 2029

(written above is an example, and could change in the future)
Spacecraft Configuration

As a result of Phase-A study, spacecraft system’s configuration and major specification are defined preliminarily.

**On-Orbit Configuration**

- **Launch Mass**: 4000kg
- **Three stages system.**
  - **Return module**: 1780kg
  - **Exploration module**: 330kg
  - **Propulsion module**: 1890kg
- **Mission Duration**: 5 years

(written above is an example, and could change in the future)
<table>
<thead>
<tr>
<th>Payload</th>
<th>Measurements</th>
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</table>
| Wide-angle multiband camera (OROCHI)                                   | • Global mapping of hydrated minerals, organics, and the spectral heterogeneity of the Martian moons  
• Characterize the material distribution around the sampling sites        |
| Telescopic camera (TENGOO)                                             | • Determine the global topography and surface structure of the Martian moons  
• Characterize the topography around the sampling sites                    |
| Gamma-ray, neutron spectrometer (MEGANE) ([provided by NASA])          | • Determine the elemental abundance beneath the surface of the Martian satellites (Provided by NASA)                                          |
| Near-infrared spectrometer (MIRS) ([provided by CNES])                | • Global mapping of minerals, molecular H$_2$O and organics of the Martian moons.  
• Characterize the material distribution around the sampling sites         |
| Light detection and ranging (LIDAR)                                   | • Determine the Phobos shape and topography                                                                                                 |
| Circum-martian dust monitor (CMDM)                                     | • Detect and monitor: 1) the circum-Martian dust ring; 2) interplanetary dust; 3) Interstellar dust                                         |
| Mass spectrum analyser (MSA)                                          | • Determine the mass and energy of ions from Phobos, Mars and Sun                                                                            |
| Rover’s payloads ([by CNES/DLR]) : Raman, radiometer, cameras          | • Determine surface composition and physical properties                                                                                      |
Two competing hypotheses are proposed for their origins:

Capture of asteroid:
- Consistent with D- or T-type IR spectra.

*Image courtesy (Hiro Kurokawa)*

in situ formation by an impact:
- Consistent with low eccentricity & inclination.

*Image courtesy (Hiro Kurokawa)*
ORIGIN OF PHOBOS AND DEIMOS

D- or T-type spectrum is consistent with the capture origin

If Phobos & Deimos are “giant impact origin”, the spectra reflect either
• impact-related “dark” glassy debris, or
• thin surface veneer of regolith, or
• result of space weathering

will be tested by MMX
• gamma-ray & neutron, sample analysis

Fraeman et al. (2012)
ORIGIN OF PHOBOS AND DEIMOS

Low eccentricity and low inclination suggest the impact origin

- **Low eccentricity** (Jacobson & Lainey, 2014)
  - Phobos: 0.001511, Deimos: 0.00027

- **Low inclination** (Jacobson & Lainey, 2014)
  - Phobos: 1.076 deg, Deimos: 1.789 deg

If Phobos & Deimos are “capture origin”...

“Gold mine” for astrophysicists!
New dynamical model to reconcile
REMOTE SENSING OBSERVATIONS

Visible & Near-infrared spectroscopy
- MIRS from LESIA, France
  - Spectrum range: 0.9-3.6 μm
  - Spatial resolution: 7 m/pix @ 20 km (tentative)

Gamma-ray & Neutron spectroscopy
- MEGANE from APL, USA
  - Elements: Mg, Fe, O, Si, Na, K, Ca, Th, U, H, C, and Cl
  - Penetration depth: up to ~1 m

Fe/Si/O differentiates achondritic (giant impact) and chondritic (capture) compositions
<table>
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<th>Expected Characteristics of Phobos Sample</th>
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<td><strong>Moon origin</strong></td>
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<tr>
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<tr>
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<tr>
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### Expected Characteristics of Phobos Sample

**38TH MEPAG (2020)**

#### Capture of Asteroid

- Outer solar system body
- Inner solar system body
- Co-accretion
- Giant impact

#### Petrology

- Analogous to carbonaceous chondrite, IDP, or cometary material
- Analogous to ordinary chondrite?
- Glassy or recrystallized igneous texture

#### Mineralogy

- Rich in oxidized and hydrous alteration phases (e.g., phyllosilicates, carbonates), amorphous silicates
- Reduced and mostly anhydrous phases (e.g., pyroxenes, olivines, sulfides)
- Un-equilibrated mixture of chondritic minerals?
- High-T igneous phases (e.g., pyroxenes, olivines), Martian crustal (evolved igneous) & mantle (high-P) phases

#### Bulk chemistry

- Chondritic, volatile-rich (e.g. high C and high H)
- Chondritic, volatile poor
- Chondritic (= ~ bulk Mars?) with nebula-derived volatile?
- Mixture of Martian crustal (mafic) and mantle-like (ultramafic) composition, possibly with impactor material (high HSE?). Degree of volatile depletion varies due to impact regime

#### Isotopes

- Carbonaceous chondrite signature (e.g., Δ17O, ε54Cr, ε50Ti, εMo, noble gases), primitive solar-system volatile signature (e.g., D/H, 15N/14N)
- Non-carbonaceous chondrite signature (e.g., Δ17O, ε54Cr, ε50Ti, εMo, noble gases), primitive (e.g., chondritic D/H, 15N/14N)?
- Bulk-Mars (?) signature (e.g., Δ17O, ε54Cr, ε50Ti, εMo), planetary volatile (e.g., intermediate D/H, low 15N/14N?)?
- Mixture of Martian and impactor (carbonaceous or non-carbonaceous) composition, highly mass fractionated planetary volatile (e.g., low D/H, low 15N/14N)?

#### Organics

- Primitive organic matter, volatile & semi-volatile organics, soluble organics?
- Non-carbonaceous signature?
- ?
- ?

*(Usui et al. Space Sci. Rev. in press)*
MARTIAN SAMPLES ON PHOBOS?

Mars impact ejecta could exist in the regolith of Phobos

- Mars ejecta on Phobos is expected to experience much lower launch velocity than Martian meteorites, preserving original information?
- Contain a variety of ancient sedimentary materials (with organics?)
  ⇒ cf. Martian meteorite = igneous rocks

Phobos regolith provides a wealth of information on the ancient surface environments of Mars

(Hyodo et al. 2019)
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Phobos regolith provides a wealth of information on the ancient surface environments of Mars

(Hyodo et al. 2019)
TWO SYNERGISTIC SAMPLING SYSTEMS

Coring & pneumatic sampling maximizes MMX sample science

**Core sampler**
Access to Phobos building blocks beneath the surface (>2 cm)

**Pneumatic sampler**
Selective sampling of Phobos surface veneer (incl. Martian samples!)
SAMPLE ANALYSIS: FLOW CHART

- ~10,000 grains for initial screening
  *FYI: ~10,000 grains = ~1 g (for ~0.3 mm size grain)*
- ~100 grains for detailed petrology, mineralogy, *in situ* isotope analyses
- ~10 to 20 grains for bulk isotope analyses

~1 g for the MMX team
>9 g for the int. community!
CONCLUSIONS

• The MMX spacecraft is scheduled to be launched in 2024, and return >10 g of Phobos regolith back to Earth in 2029

• The origin(s) of Phobos and Deimos has been in debate: captured asteroid or in situ formation by impact

• MMX will provide clues to their origins and offer an opportunity to directly explore the building blocks, juvenile crust/mantle components, and late accreted volatiles of Mars

MMX will constrain the initial condition of the Mars-moon system, and shed light on the source, timing and delivery process of water (& organics) into the inner rocky planets