# AN OVERVIEW OF MARS OBSERVATION PLANNED BY THE MARTIAN MOONS EXPLORATION (MMX)

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**Introduction:**

Mars is the planet most similar to the Earth in the solar system in that it has a solid surface and an appreciable amount of atmosphere with moderate temperatures, and that there is evidence of liquid water activity, volcanic activity and possible habitability. In recent decades many Mars missions have been conducted to reveal the planet's evolution and the current climate. Tough the current Mars is a dry and cold world that includes a significant amount of frozen surface/subsurface water resources, geological evidence obtained by the spacecraft suggests that Mars may have sustained a wet and warm world in the past under the influence of a greenhouse effect (e.g., Ramirez and Craddock 2018). The transition to the current climate should have been driven by a combination of various physical/chemical processes, such as degassing, escape of volatiles to space, loss of the intrinsic magnetic field, exchange of water and other volatiles between the atmosphere and the crust, photochemistry, radiative transfer and atmospheric circulation. A possible example of strong coupling between different processes is the recent discovery of the apparent response of escaping ion fluxes to the upward transport of dust and water in the lower atmosphere (Heavens et al. 2018). The growing global interest in the history of the Martian surface environment motivated us to develop a Mars observation plan in the MMX (Martian Moons eXploration) mission aiming to disentangle the coupling among different processes, thereby assessing the roles of short-term elementary processes in the atmosphere and in the circum-Mars space in the long-term evolution of the Martian environment

**The Martian Moons eXploration mission:**

MMX is the third sample return mission of JAXA (Japan Aerospace Exploration Agency) (Kuramoto et al. 2021). The spacecraft will conduct close-up observations of the Martian satellites Phobos and Deimos, collect samples from Phobos, and bring them back to the Earth to reveal the origin of the two moons. In addition, MMX will conduct remote observations of the Martian atmosphere and surface and in situ measurements of volatiles escaping to space during the 3-year Mars orbiting phase. We take advantage of MMX's unique orbit around Mars: the equatorial high-altitude orbit will enable continuous remote monitoring of short-timescale phenomena in the atmosphere and increase opportunities of the measurement of low-energy ion outflows in the shadows of Mars and Phobos. The samples brought back to the Earth are expected to contain particles ejected from the Martian surface by asteroid impacts, from which information on early Mars will be retrieved. Combining this broad range of information will allow for an integrated understanding of Mars system that consists of Mars, its moons, and the circum-Mars space. For example, the transport of water across the atmosphere from the surface to space will be tracked with an infrared imaging spectrometer and an ion spectrometer, and this knowledge of water transport, combined with isotopic fractionation analysis of returned Mars samples, will allow us to develop a scenario of the environmental evolution of Mars. The spacecraft will be launched in 2024, put into a Martian orbit in 2025, stay in orbit around Mars until 2028, and return to the Earth in 2029.

Currently, quite a few Mars missions are ongoing: Mars Odyssey, Mars Express (MEX), Mars Reconnaissance Orbiter (MRO), Curiosity rover, Mangalyaan orbiter, Chinese Tianwen 1 mission, Mars Atmosphere and Volatile Evolution (MAVEN), ExoMars Trace Gas Orbiter (EMTGO), and InSight lander. The Hope orbiter planned by United Arab Emirates has started remote observations of the Martian atmosphere from a high-altitude equatorial orbit since 2021. Mars sample return (MSR) mission is also currently under consideration to bring back samples from Mars (Beaty et al. 2019). The Mars observations in MMX are complementary to those missions in several aspects, such as the observation wavelength, the spatial resolution in global imaging, the sensitivity to low energies and the mass resolution in ion measurements, and the sample return to the Earth.

**Mission definition regarding the Martian sur-**

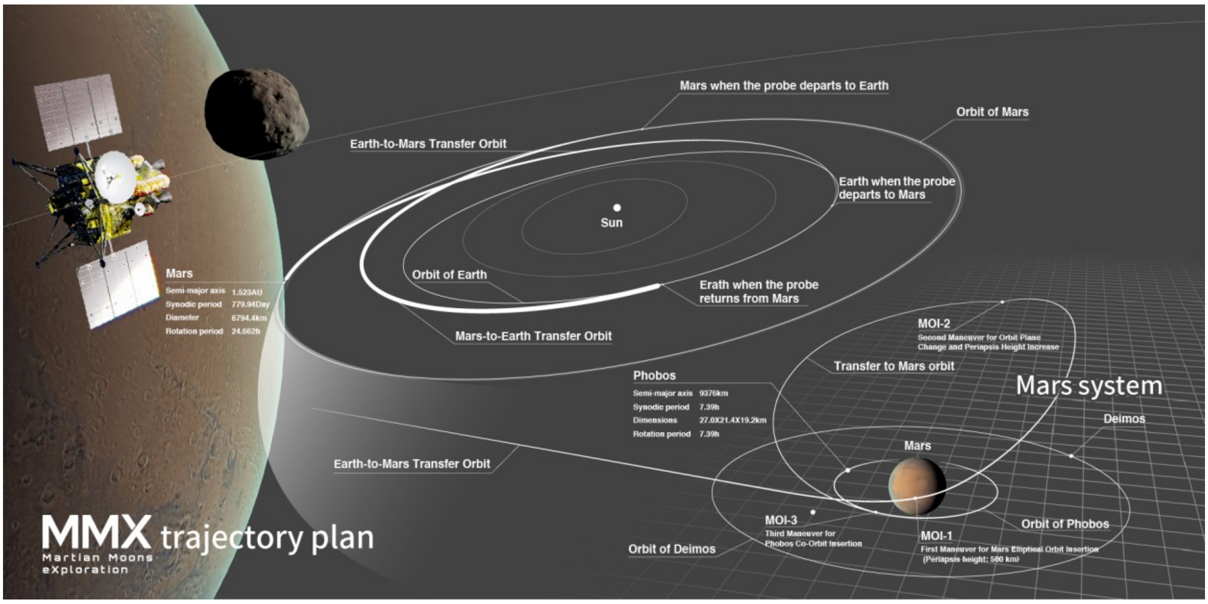


**Figure 1 A trajectory plan of MMX (http://www.mmx.jaxa.jp/en/gallery/)**

**face environment:**

We are motivated to plan MMX by the growing global interest in the evolution of the Martian environment as mentioned in the “Introduction” section. This is reflected in one of the scientific goals (SGs) of MMX. The first of SGs (SG-1) is related to studies on the Martian moons and the understanding of the planetary system formation and material transport in the solar system (Kuramoto et al. 2021). The second scientific goal of the MMX (SG-2) is:

- From the viewpoint of the Martian moons, clarify the driving mechanism of the transition of the Mars-moon system and add new knowledge to the evolution history of Mars.

What is crucial for studies on the evolution of the planetary surface environment is to directly observe the history as geologists have reconstructed the history of the terrestrial environment from rock or sediment samples. Another important approach is to understand the phenomena seen in the atmosphere and circum-Mars space today and infer the past from them. Thus, SG-2 is broken down into three medium objectives (MOs). Ogohara et al. (2022) provides an overview of the relationship between the SG, MOs and related science themes. The first MO is associated with the surface processes of the airless small body (i.e., Phobos) and the other two MOs cover the Mars environmental evolution:

- MO-2.2: add new findings and constraints on the history of changes in the Martian surface,
- MO-2.3: constrain the mechanisms of material circulation in the Martian atmosphere affecting the transitions in the Martian climate.

One of the methods to achieve MO-2.2 is to restore the paleoclimate changes from Martian samples that have been accumulated on the Phobos surface (Hyodo et al. 2019). The other is the estimation of the past atmospheric escape based on the present observations. They are expected to be achieved by analyses of Martian samples on Phobos returned to Earth and observations of the atmospheric escape (Usui et al. 2020). MO-2.3 covers understanding of the efficient upward transport processes required for efficient $H_2O$ escape from the top of the atmosphere. MO-2.3 is expected to be achieved by continuous full-disk monitoring of Mars with visible and infrared wavelengths. Observations of distributions of dust, ice clouds, and water vapor with higher temporal and spatial resolutions than the previous observations are necessary for MO-2.3.

**Mars observation:**

*Orbit.* MMX will travel in a cruising orbit to Mars for 1 year, observe Mars and its moons for 3 years from 2025 to 2028, and eventually bring back collected samples to the Earth after a 1-year journey (Fig. 1). During most of its 3-year mission, MMX trajectory will be in Quasi-Satellite Orbit (QSO) around Phobos, which is very similar to Phobos orbit around Mars: nearly equatorial and circular, with a period of 7h40’ and distance of about 9,376 km from the Mars center (about 6000 km from the Mars surface). In operation on Mars Moon proximity, remote sensing for atmospheric phenomena and in situ measurement for atmosphere escaping are continuously conducted on QSOs as a home position throughout the mission from Mars Orbit Insertion (MOI).

Mars observation by MMX from the Martian equatorial plane (inclination of~1°) has several assets. This circular orbit is relatively close to Mars when comparing to the areostationary orbit. MMX orbital motion (0.013°/s with the period of 7h40') will be faster than the rotational period of Mars (0.004°/s). As a consequence, the difference of rotation rate drifts the subsatellite point around 0.009°/s. In 7h40', subsatellite point shifts ~248° eastward. After three orbits of 7h40' (~23 h), subsatellite point has shifted of ~744°=2 × 360°+24°, so MMX is located above a longitude 24° east of that three orbits ago. Quasi-areostationary orbiters are innovative platforms for space-born Mars science, as has been geostationary satellite imagery which revolutionized Earth weather forecasting from 1970s. The first equatorial orbiters will blaze a trail for the continuous remote sensing of the Martian atmosphere. Remote sensing from high orbit will enable to work in conjunction with satellites in polar or eccentric low-altitude orbits, which provide truly global coverage and synergistic perspective. From the equatorial plane, it is however noted that the apparent visible disk of Mars takes up a field of view of about~43°. The coverage reaches up to approximately 68° latitude. In addition, the equatorial orbit of MMX will essentially increase opportunities to directly measure the low-energy outflow of ionospheric ions from Mars in the inner magnetosheath, which has been poorly understood so far.

*Instruments.* The mass spectrum analyzer (MSA) is a scientific instrument onboard the MMX spacecraft, which consists of an ion energy mass spectrometer and two magnetometers (Yokota et al. 2021). The ion spectrometer measures distribution functions of low-energy (<10 s keV) ions and their mass/charge distributions using a top-hat electrostatic energy analysis and a linear-electric-field time-of-fight mass analysis. The fluxgate magnetometers measure the vector magnetic field of the solar wind, which is occasionally perturbed by Mars and possibly Phobos in their neighborhood. The MSA experiment is designed to perform in situ observations of secondary ions emitted from Phobos, water ions generated from the Phobos torus if exists, and escaping ions from the Martian atmosphere with monitoring the solar wind. The mass resolution of M/ Δ M~100, because the MSA will measure heavy ions and their isotopes coming from the Martian atmosphere to estimate the amount of the atmospheric escape. MMX will be located in the Mars shadow (eclipse) at approximately half of the year. In these periods, MMX will measure escaping ions in the magnetotail. In other periods, MMX will observe the solar wind. Seasonal variation of the MMX orbit with respect to the magnetotail can allow us to observe the longitudinal–latitudinal structure of escaping ions at 6000 km distance from Mars.

Optical radiometer composed of chromatic imagers (OROCHI) is designed for capturing spectral features of Phobos from ultraviolet to near-infrared wavelengths with 7 wide-angle bandpass imagers and 1 panchromatic imager. Detailed information of design and performance of OROCHI is introduced in Kameda et al. (2021). The field of view (FOV) of each imager is > 1 rad and the instantaneous FOV (iFOV) is 0.4 mradian. Because of the wide FOV, OROCHI can capture whole disk of Mars in its FOV from the Phobos altitude with the pixel resolution of 2.4 km. Since the orbit of MMX is similar to the Phobos orbit, which is almost a circular orbit around Mars, OROCHI will observe Mars from almost same altitude (~6000 km), and thus it will provide images with a stable spatial resolution. The dataset from OROCHI is similar to those from a geostationary weather satellite whose spatial and temporal resolution are the order of 1 km and 10 min, respectively. Also, thanks to its wide FOV, OROCHI can observe a wide range of local time from morning to evening in one observation. It will also give a lot of information about local time dependence or morning–evening symmetry/asymmetry. The center wavelengths of the OROCHI bandpass filters are 390 nm, 480 nm, 550 nm, 650 nm, 730 nm, 860 nm, and 950 nm, and designed signal-to-noise (S/N) ratio for spectral analysis (i.e., band ratios) is 100 (Kameda et al. 2021). For Mars observation, the blue and red bands will be mainly used for monitoring atmospheric dynamics. Dust and water ice clouds can be roughly distinguished based on a difference in brightness between the two bands. The high SN ratio is enough to resolve the difference in the photometrical properties between dust and water ice (c.f. Bell et al. 2009). The near-infrared band (950 nm) will be also important to connect the OROCHI images and MIRS data since the wavelength is commonly used by both instruments, then more detailed spectral analysis will be possible.

Telescopic Nadir imager for GeOmOrphology (TENGOO) is a panchromatic (370–850 nm) imager with a quite high spatial resolution, <6 μ-radian/pixel, which is 60 times higher than that for OROCHI. The high spatial resolution allows to observe the Martian surface with a resolution of 35 m/pixel from the altitude of Phobos, thus we can analyze sub-km scale atmospheric phenomena from TENGOO images. TENGOO's FOV is 0.82×1.1°, which corresponds to 86.5×115.5 km region in one TENGOO FOV when observing Mars from the QSO. Same as OROCHI, the most significant advantage of TENGOO observation is that TENGOO can conduct a sequential observation for several hours which is critical for understanding short timescale atmospheric phenomena on Mars. Tanks to the high spatial resolution of TENGOO, we may track sub-km scale dust flows, and then we will be able to retrieve a local wind distribution in the FOV of TENGOO by tracking modifications of clouds and dust events.

MMX InfraRed Spectrometer (MIRS) is a push-broom imaging spectrometer in the near-infrared spectral range (0.9 to 3.6 μm). MIRS detector is a 2D array providing an image of a strip in one spatial direction with the spectrum of each point in the spectral direction. A second spatial direction is provided by the instrument line of sight in the along-track direction of MMX. MIRS FOV is ±1.65° and while targeting a spatial resolution of 10 km on Mars, MIRS expected geometric resolution on Mars from QSO is ~2 km so spatial binning can be implemented to increase signal-to-noise ratio and decrease data volume. MIRS has a spectral resolution of about 20 nm and a targeted signal-to-noise ratio above 100 for features of interest. Further detailed information on the instrument can be found in Barucci et al. (2021). MIRS will also perform limb observations to obtain information on Martian atmosphere at high vertical resolution.

MIRS observations will be used to constrain transport processes for dust and water in the Martian atmosphere, observations of the equatorial to mid-latitude distributions of dust storms, water ice clouds and water vapor. $CO_2$ (and thus pressure) will be monitored through $CO_2$ 2.0 µm band. Water vapor will be monitored on a daily basis using its 2.6 µm band (Maltagliati et al. 2008) and water ice clouds through their spectral features between 0.9 and 3.6 µm (Vincendon et al. 2011). MIRS will be able to detect CO and $O_2$ dayglow with their 2.35-µm and 1.27-µm bands, respectively. MIRS will also provide monitoring of the atmospheric dust content and of water adsorbed in the surface regolith.

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