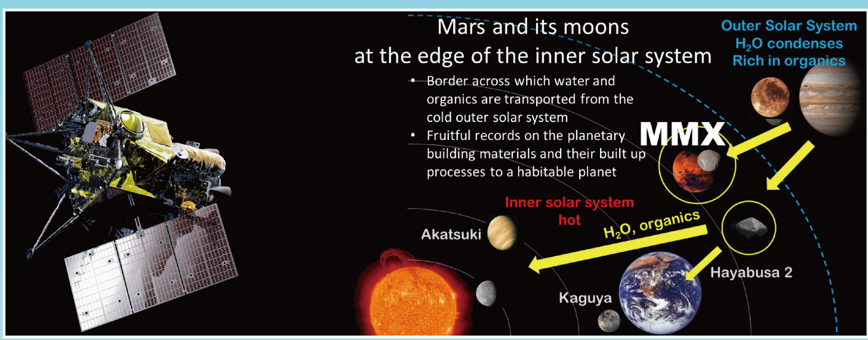
Earth, Planets and Space

Martian Moons eXploration: The scientific investigations of Mars and its moons



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Genda *et al. Earth, Planets and Space (2024) 76:8*
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PREFACE

Open Access

Special issue "Martian Moons eXploration: the scientific investigations of Mars and its moons"

Hidenori Genda[1*], Tomohiro Usui[2], Nancy L. Chabot[3], Ramses Ramirez[4] and Keiji Ohtsuki[5]

Martian Moons eXploration (MMX) marks the third sample return mission led by the Japan Aerospace Exploration Agency (JAXA), succeeding the Hayabusa and Hayabusa 2 missions. The MMX spacecraft aims to extensively observe two Martian moons (Phobos and Deimos) and Mars over 3 years, and collect samples from Phobos for return to Earth. The major scientific objectives of the MMX mission are to solve the origin of the two moons, to elucidate the early Solar System evolution, and to explore the evolutionary processes of both moons and Mars surface environment. This first special issue for the MMX mission is dedicated to the current status of the MMX mission, such as the science instruments aboard MMX, the mission plan, and the strategies to achieve the scientific objectives.

Kuramoto et al. (2022) overviewed the current design of the MMX mission, focusing on the scientific objectives and the mission requirements. To achieve those objectives, the MMX spacecraft is equipped with 7 scientific instruments, 1 rover, and 2 sampling systems. Kameda et al. (2021) described a telescopic camera, TENGOO (TElescopic Nadir imager for GeOmOrphology), and wide-angle multiband camera, OROCHI (Optical RadiOmeter composed of CHromatic Imagers). Senshu et al. (2021) presented a laser altimeter, LIDAR (LIgiht Detection And Ranging). Barucci et al. (2021) presented a near-infrared spectrometer, MIRS (MMX InfraRed Spectrometer), which is built at LESIA-Paris Observatory. Chabot et al. (2021) presented a NASA-funded gamma-ray and neutron spectrometer, MEGANE (Mars-moon Exploration with GAmma rays and NEutrons). Yokota et al. (2021) described an ion mass spectrometer, MSA (Mass Spectrum Analyzer). Kobayashi et al. (2018) described a dust counter, CMDM (Circum-Martian Dust Monitor), and its implication was presented in Krüger et al. (2021). The MMX spacecraft is also equipped with a rover developed by CNES and DLR (Michel et al. 2022) with a Raman spectrometer, RAX (Cho et al. 2021). Two independent sampling systems using coring and pneumatic samplers will be employed on the MMX spacecraft (Usui et al. 2020).

Nakamura et al. (2021) summarized the current scientific operation plan for 3 years, including the close-up observations of Phobos, rover delivery to Phobos, two touch down events for sample collection, observation of Mars (Ogohara et al. 2022), and the flyby observation of Deimos. Matsumoto et al. (2021) reviewed recent geodetic observations of Phobos, and showed the strategies for the geodetic observations during the MMX mission. High-resolution shape models of Phobos and Deimos were presented in Ernst et al. (2023). Fujiya et al. (2021) presented the design of analytical protocols for the returned Phobos samples to reveal the origin of the Martian moons as well as the evolution of the Mars-moons system.

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In addition, Miyamoto et al. (2021) reviewed the surface environment of Phobos and showed the development of simulated soil materials of Phobos. Takemura et al. (2021) summarized typical geological features of Phobos and discussed the topographic irregularities and the engineering safety for the landing sites. Sefton-Nash et al. (2021) discussed the possibility of Phobos for an exploration platform on Phobos in the future.

While JAXA leads the MMX mission, some instruments, observational planning and execution are shaped by extensive international collaborations, fostering a collective effort in advancing our understanding of Mars and its moons system. The new knowledge brought forth by the MMX mission is poised to carve out new horizons in future research and exploration activities. The pursuit of the unknown will continue to drive the journey of science and exploration.

Author contribution

All authors of this article served as guest editors for this special issue. HG drafted the manuscript. All authors read and approved the final manuscript.

Data availability

Not applicable.

Declarations

Competing interests

The authors declare that they have no competing interests.

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FRONTIER LETTER **Open Access**

Martian moons exploration MMX: sample return mission to Phobos elucidating formation processes of habitable planets

Kiyoshi Kuramoto*, Yasuhiro Kawakatsu, Masaki Fujimoto, Akito Araya, Maria Antonietta Barucci, Hidenori Genda, Naru Hirata, Hitoshi Ikeda, Takeshi Imamura, Jörn Helbert, Shingo Kameda, Masanori Kobayashi, Hiroki Kusano, David J. Lawrence, Koji Matsumoto, Patrick Michel, Hideaki Miyamoto, Tomokatsu Morota, Hiromu Nakagawa, Tomoki Nakamura, Kazunori Ogawa, Hisashi Otake, Masanobu Ozaki, Sara Russell, Sho Sasaki, Hirotaka Sawada, Hiroki Senshu, Shogo Tachibana, Naoki Terada, Stephan Ulamec, Tomohiro Usui, Koji Wada, Sei-ichiro Watanabe and Shoichiro Yokota

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Abstract

Martian moons exploration, MMX, is the new sample return mission planned by the Japan Aerospace Exploration Agency (JAXA) targeting the two Martian moons with the scheduled launch in 2024 and return to the Earth in 2029. The major scientific objectives of this mission are to determine the origin of Phobos and Deimos, to elucidate the early Solar System evolution in terms of volatile delivery across the snow line to the terrestrial planets having habitable surface environments, and to explore the evolutionary processes of both moons and Mars surface environment. To achieve these objectives, during a stay in circum-Martian space over about 3 years MMX will collect samples from Phobos along with close-up observations of this inner moon and carry out multiple flybys of Deimos to make comparative observations of this outer moon. Simultaneously, successive observations of the Martian atmosphere will also be made by utilizing the advantage of quasi-equatorial spacecraft orbits along the moons' orbits.

Keywords: Phobos, Deimos, Mars, Sample return mission, Early Solar System, Habitable planet

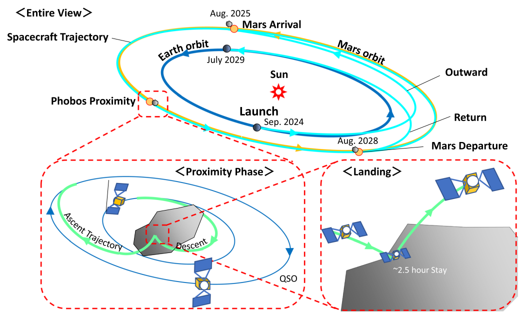

Fig. 2

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FULL PAPER **Open Access**

Modelling cometary meteoroid stream traverses of the Martian Moons eXploration (MMX) spacecraft en route to Phobos

Harald Krüger*, Masanori Kobayashi, Peter Strub, Georg-Moragas Klostermeyer, Maximilian Sommer, Hiroshi Kimura, Eberhard Grün and Ralf Srama

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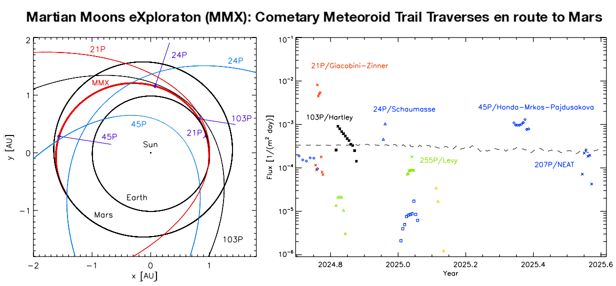
Abstract

The Martian Moons Exploration (MMX) spacecraft is a JAXA mission to Mars and its moons Phobos and Deimos. MMX will be equipped with the Circum-Martian Dust Monitor (CMDM) which is a newly developed light-weight (650 g) large area (1 m^2) dust impact detector. Cometary meteoroid streams (also referred to as trails) exist along the orbits of comets, forming fine structures of the interplanetary dust cloud. The streams consist predominantly of the largest cometary particles (with sizes of approximately 100 μm to 1 cm) which are ejected at low speeds and remain very close to the comet orbit for several revolutions around the Sun. The Interplanetary Meteoroid Environment for eXploration (IMEX) dust streams in space model is a new and recently published universal model for cometary meteoroid streams in the inner Solar System. We use IMEX to study the detection conditions of cometary dust stream particles with CMDM during the MMX mission in the time period 2024 to 2028. The model predicts traverses of 12 cometary meteoroid streams with fluxes of 100 μm and bigger particles of at least $10^{-3} m^{-2} day^{-1}$ during a total time period of approximately 90 days. The highest flux of 0.15 $m^{-2} day^{-1}$ is predicted for comet 114P/Wiseman-Skiff in October 2026. With its large detection area and high sensitivity CMDM will be able to detect cometary meteoroid streams en route to Phobos. Our simulation results for the Mars orbital phase of MMX also predict the occurrence of meteor showers in the Martian atmosphere which may be observable from the Martian surface with cameras on board landers or rovers. Finally, the IMEX model can be used to study the impact hazards imposed by meteoroid impacts onto large-area spacecraft structures that will be particularly necessary for crewed deep space missions.

Keywords: Comets, Meteoroid trails, Meteoroid streams, Interplanetary dust, Martian moons, Phobos, Deimos, Martian Moons Exploration, MMX



Graphical abstract

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FULL PAPER **Open Access**

Analytical protocols for Phobos regolith samples returned by the Martian Moons eXploration (MMX) mission

Wataru Fujiya*, Yoshihiro Furukawa, Haruna Sugahara, Mizuho Koike, Ken-ichi Bajo, Nancy L. Chabot, Yayoi N. Miura, Frederic Moynier, Sara S. Russell, Shogo Tachibana, Yoshinori Takano, Tomohiro Usui and Michael E. Zolensky

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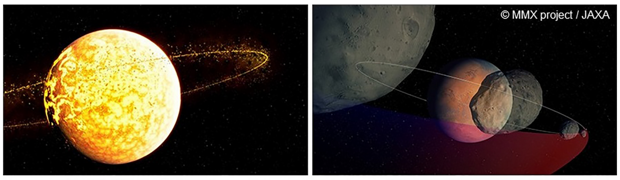
Abstract

Japan Aerospace Exploration Agency (JAXA) will launch a spacecraft in 2024 for a sample return mission from Phobos (Martian Moons eXploration: MMX). Touchdown operations are planned to be performed twice at different landing sites on the Phobos surface to collect > 10 g of the Phobos surface materials with coring and pneumatic sampling systems on board. The Sample Analysis Working Team (SAWT) of MMX is now designing analytical protocols of the returned Phobos samples to shed light on the origin of the Martian moons as well as the evolution of the Mars–moon system. Observations of petrology and mineralogy, and measurements of bulk chemical compositions and stable isotopic ratios of, e.g., O, Cr, Ti, and Zn can provide crucial information about the origin of Phobos. If Phobos is a captured asteroid composed of primitive chondritic materials, as inferred from its reflectance spectra, geochemical data including the nature of organic matter as well as bulk H and N isotopic compositions characterize the volatile materials in the samples and constrain the type of the captured asteroid. Cosmogenic and solar wind components, most pronounced in noble gas isotopic compositions, can reveal surface processes on Phobos. Long- and short-lived radionuclide chronometry such as ^{53}Mn–^{53}Cr and ^{87}Rb–^{87}Sr systematics can date pivotal events like impacts, thermal metamorphism, and aqueous alteration on Phobos. It should be noted that the Phobos regolith is expected to contain a small amount of materials delivered from Mars, which may be physically and chemically different from any Martian meteorites in our collection and thus are particularly precious. The analysis plan will be designed to detect such Martian materials, if any, from the returned samples dominated by the endogenous Phobos materials in curation procedures at JAXA before they are processed for further analyses.

Keywords: MMX, Sample analyses, Mineralogy, Petrology, Chemical composition, Isotopic composition, Organic matter



Graphical abstract

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FULL PAPER **Open Access**

MIRS: an imaging spectrometer for the MMX mission

Maria Antonietta Barucci*, Jean-Michel Reess, Pernelle Bernardi, Alain Doressoundiram, Sonia Fornasier, Michel Le Du, Takahiro Iwata, Hiromu Nakagawa, Tomoki Nakamura, Yves André, Shohei Aoki, Takehiko Arai, Elisa Baldit, Pierre Beck, Jean-Tristan Buey, Elisabet Canalias, Matthieu Castelnau, Sebastien Charnoz, Marc Chaussidon, Fréderic Chapron, Valerie Ciarletti, Marco Delbo, Bruno Dubois, Stephane Gauffre, Thomas Gautier, Hidenori Genda, Rafik Hassen-Khodja, Gilles Hervet, Ryuki Hyodo, Christian Imbert, Takeshi Imamura, Laurent Jorda, Shingo Kameda, Driss Kouach, Toru Kouyama, Takeshi Kuroda, Hiroyuki Kurokawa, Laurent Lapaw, Jeremie Lasue, Laetitia Le Deit, Aurélien Ledot, Cedric Leyrat, Bertrand Le Ruyet, Moe Matsuoka, Frederic Merlin, Hideaki Miyamoto, Frederic Moynier, Napoleon Nguyen Tuong, Kazunori Ogohara, Takahito Osawa, Jérôme Parisot, Laurie Pistre, Benjamin Quertier, Sean N. Raymond, Francis Rocard, Takeshi Sakanoi, Takao M. Sato, Eric Sawyer, Fériel Tache, Sylvain Trémolières, Fuminori Tsuchiya, Pierre Vernazza and Didier Zeganadin

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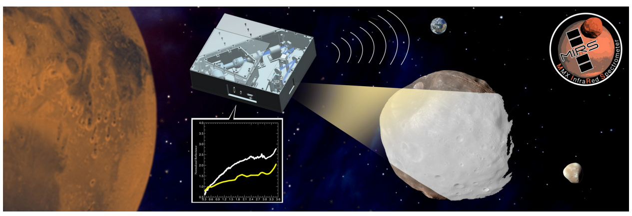
Abstract

The MMX infrared spectrometer (MIRS) is an imaging spectrometer onboard MMX JAXA mission. MMX (Martian Moon eXploration) is scheduled to be launched in 2024 with sample return to Earth in 2029. MIRS is built at LESIA-Paris Observatory in collaboration with four other French laboratories, collaboration and financial support of CNES and close collaboration with JAXA and MELCO. The instrument is designed to fully accomplish MMX's scientific and measurement objectives. MIRS will remotely provide near-infrared spectral maps of Phobos and Deimos containing compositional diagnostic spectral features that will be used to analyze the surface composition and to support the sampling site selection. MIRS will also study Mars atmosphere, in particular spatial and temporal changes such as clouds, dust and water vapor.

Keywords: MIRS, MMX, Imaging spectrometer, Phobos, Deimos, Mars



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FULL PAPER **Open Access**

Small-scale topographic irregularities on Phobos: image and numerical analyses for MMX mission

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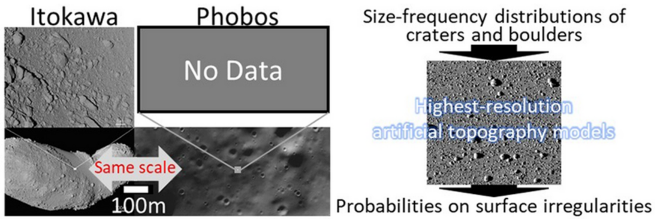
Abstract

The mothership of the Martian Moons eXploration (MMX) will perform the first landing and sampling on the surface of Phobos. For the safe landing, the 2.1-m-wide mothership of the MMX should find a smooth surface with at most 40 cm topographic irregularity, however, whose abundance or even existence is not guaranteed based on current knowledge. We studied the highest resolution (a few meters per pixel) images of Phobos for possible topographic irregularities in terms of boulder (positive relief feature) and crater distributions. We find that the spatial number densities of positive relief features and craters can vary significantly, indicating that the surface irregularities vary significantly over the entire surface. We extrapolate the size-frequency distributions of positive relief features to evaluate the surface roughness below the image resolution limit. We find that the probabilities that topographic irregularities are <40 cm for the areas of 4×4 m and 20×20 m are $>33\%$ and $<1\%$ for boulder-rich areas and $>88\%$ and $>13\%$ for boulder-poor areas, respectively, even for the worst-case estimates. The estimated probabilities largely increase when we reduce the assumed number of positive relief features, which are more realistic cases. These indicate high probabilities of finding a smooth enough place to land on Phobos' surface safely.

Keywords: MMX, Phobos, Deimos, Landing, Topography, Roughness



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FULL PAPER **Open Access**

Surface environment of Phobos and Phobos simulant UTPS

Hideaki Miyamoto*, Takafumi Niihara, Koji Wada, Kazunori Ogawa, Hiroki Senshu, Patrick Michel, Hiroshi Kikuchi, Ryodo Hemmi, Tomoki Nakamura, Akiko M. Nakamura, Naoyuki Hirata, Sho Sasaki, Erik Asphaug, Daniel T. Britt, Paul A. Abell, Ronald-Louis Ballouz, Olivier S. Banouin, Nicola Baresi, Maria A. Barucci, Jens Biele, Matthias Grott, Hideitsu Hino, Peng K. Hong, Takane Imada, Shingo Kameda, Makito Kobayashi, Guy Libourel, Katsuro Mogi, Naomi Murdoch, Yuki Nishio, Shogo Okamoto, Yuichiro Ota, Masatsugu Otsuki, Katharina A. Otto, Naoya Sakatani, Yuta Shimizu, Tomohiro Takemura, Naoki Terada, Masafumi Tsukamoto, Tomohiro Usui and Konrad Willner

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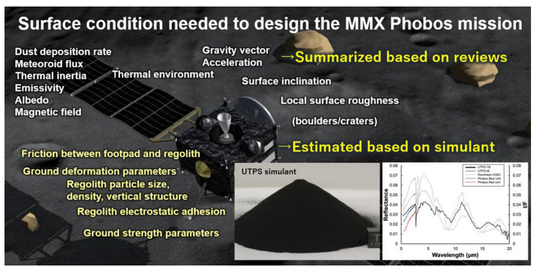
Abstract

The Martian Moons eXploration (MMX) mission will study the Martian moons Phobos and Deimos, Mars, and their environments. The mission scenario includes both landing on the surface of Phobos to collect samples and deploying a small rover for in situ observations. Engineering safeties and scientific planning for these operations require appropriate evaluations of the surface environment of Phobos. Thus, the mission team organized the Landing Operation Working Team (LOWT) and Surface Science and Geology Sub-Science Team (SSG-SST), whose view of the Phobos environment is summarized in this paper. While orbital and large-scale characteristics of Phobos are relatively well known, characteristics of the surface regolith, including the particle size-distributions, the packing density, and the mechanical properties, are difficult to constrain. Therefore, we developed several types of simulated soil materials (simulant), such as UTPS-TB (University of Tokyo Phobos Simulant, Tagish Lake based), UTPS-IB (Impact-hypothesis based), and UTPS-S (Simpler version) for engineering and scientific evaluation experiments.

Keywords: MMX, Phobos, Deimos, Surface environment, Simulant



Graphical abstract

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FULL PAPER **Open Access**

Visibility analysis of Phobos to support a science and exploration platform

Elliot Sefton-Nash*, Guillaume Thébault, Olivier Witasse, Detlef Koschny, Beatriz Sánchez-Cano and Alejandro Cardesín-Moinelo

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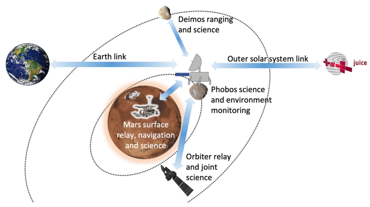
Abstract

The surfaces of the Martian moons, Phobos and Deimos may offer a stable environment for long-term operation of platforms. We present a broad assessment of potential scientific investigations, as well as strategic and operational opportunities offered by long-term operation of an instrumented lander. Studies using observations of Mars' moons, and the detailed new findings expected from the JAXA Martian Moons eXploration (MMX) mission, International Mars Sample Return (MSR) Campaign and other upcoming Mars missions, provide a driver for feasibility and trade studies for follow-on missions that would build on the knowledge gain from those missions. We discuss the scientific questions and operational objectives that may be pertinent for landed platforms on the martian moons, including (1) monitoring and scientific investigations of Mars' surface and atmosphere, (2) scientific investigations of the martian moons, (3) monitoring and scientific investigations of the space environment, (4) data relay for Mars surface assets or interplanetary missions and 5) use in a Mars navigation/positioning system. We present results from visibility calculations performed using the SPICE observation geometry system for space science missions, and a Phobos shape model. We compute as a function of location on Phobos, visibility quantities that are most relevant to science and operational objectives. These include visibility from Phobos of the Sun, Earth, Mars surface and atmosphere, Deimos, and Jupiter. We also consider occultation events by the Mars atmosphere of Earth and Deimos that may provide opportunities for radio science. Calculations are performed for a study period spanning one Mars year in a hypothetical future operational scenario (1 Jan 2030–18 Nov 2031). We combine visibility metrics to identify locations on Phobos most suitable for long-term operation of a platform. We find the Mars-facing side of Phobos, and limited areas on the leading and trailing sides, satisfy the most requirements defined for Mars and Phobos science, space environment monitoring, and data relay/navigation. We demonstrate that compliance with requirements related to visibility of Mars and its atmosphere are not mutually exclusive with those that are better satisfied on Phobos' anti-Mars side, such as those aided by maximizing their cumulative view factor to the ecliptic plane (i.e. visibility to the Sun, Earth or outer solar system). Finally, our methodology allows to assess the extent to which combined visibility metrics can meet mission requirements. The process we describe can be used to support landing site identification and selection on planets, moons and small bodies.

Keywords: Phobos, Deimos, Mars, Platform, Visibility



Graphical abstract

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FULL PAPER **Open Access**

In situ observations of ions and magnetic field around Phobos: the mass spectrum analyzer (MSA) for the Martian Moons eXploration (MMX) mission

Shoichiro Yokota*, Naoki Terada, Ayako Matsuoka, Naofumi Murata, Yoshifumi Saito, Dominique Delcourt, Yoshifumi Futaana, Kanako Seki, Micah J. Schaible, Kazushi Asamura, Satoshi Kasahara, Hiromu Nakagawa, Masaki N. Nishino, Reiko Nomura, Kunihiro Keika, Yuki Harada and Shun Imajo

Earth, Planets and Space 2021, **73**:216 DOI: 10.1186/s40623-021-01452-x
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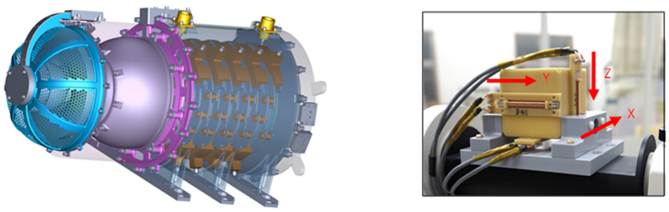
Abstract

The mass spectrum analyzer (MSA) will perform in situ observations of ions and magnetic fields around Phobos as part of the Martian Moons eXploration (MMX) mission to investigate the origin of the Martian moons and physical processes in the Martian environment. MSA consists of an ion energy mass spectrometer and two magnetometers which will measure velocity distribution functions and mass/charge distributions of low-energy ions and magnetic field vectors, respectively. For the MMX scientific objectives, MSA will observe solar wind ions, those scattered at the Phobos surface, water-related ions generated in the predicted Martian gas torus, secondary ions sputtered from Phobos, and escaping ions from the Martian atmosphere, while monitoring the surrounding magnetic field. MSA will be developed from previous instruments for space plasma missions such as Kaguya, Arase, and BepiColombo/Mio to contribute to the MMX scientific objectives.

Keywords: Martian Moons eXploration (MMX), Phobos, Mars, Mass spectrum analyzer, Magnetometer



Ion energy mass spectrometer & Magnetometers

Graphical abstract

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FULL PAPER — Open Access

MEGANE investigations of Phobos and the Small Body Mapping Tool

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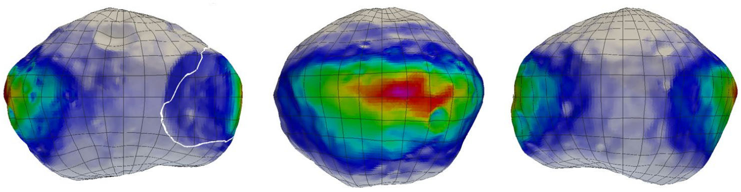
Abstract

The MEGANE instrument onboard the MMX mission will acquire gamma-ray and neutron spectroscopy data of Phobos to determine the elemental composition of the martian moon and provide key constraints on its origin. To produce accurate compositional results, the irregular shape of Phobos and its proximity to Mars must be taken into account during the analysis of MEGANE data. The MEGANE team is adapting the Small Body Mapping Tool (SBMT) to handle gamma-ray and neutron spectroscopy investigations, building on the demonstrated record of success of the SBMT being applied to scientific investigations on other spacecraft missions of irregularly shaped bodies. This is the first application of the SBMT to a gamma-ray and neutron spectroscopy dataset, and the native, three-dimensional foundation of the SBMT is well suited to MEGANE's needs. In addition, the SBMT will enable comparisons between the MEGANE datasets and other datasets of the martian moons, including data from previous spacecraft missions and MMX's multi-instrument suite.

Keywords: Phobos, MMX, MEGANE, Gamma-ray spectroscopy, Neutron spectroscopy, Martian moons



Graphical abstract

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FULL PAPER — Open Access

Design of telescopic nadir imager for geomorphology (TENGOO) and observation of surface reflectance by optical chromatic imager (OROCHI) for the Martian Moons Exploration (MMX)

Shingo Kameda*, Masanobu Ozaki, Keigo Enya, Ryota Fuse, Toru Kouyama, Naoya Sakatani, Hidehiko Suzuki, Naoya Osada, Hiroki Kato, Hideaki Miyamoto, Atsushi Yamazaki, Tomoki Nakamura, Takaya Okamoto, Takahiro Ishimaru, Peng Hong, Ko Ishibashi, Takeshi Takashima, Ryoya Ishigami, Cheng-Ling Kuo, Shinsuke Abe, Yuya Goda, Hajime Murao, Saori Fujishima, Tsubasa Aoyama, Keiji Hagiwara, Satoko Mizumoto, Noriko Tanaka, Kousuke Murakami, Miho Matsumoto, Kenji Tanaka and Hironobu Sakuta

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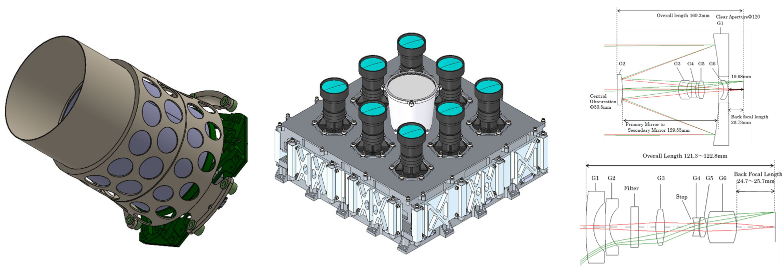
Received: 20 January 2021, Accepted: 12 June 2021, Published: 14 December 2021

Abstract

The JAXA's Martian Moons Exploration (MMX) mission is planned to reveal the origin of Phobos and Deimos. It will remotely observe both moons and return a sample from Phobos. The nominal instruments include the TElescopic Nadir imager for GeOmOrphology (TENGOO) and Optical RadiOmeter composed of CHromatic Imagers (OROCHI). The scientific objective of TENGOO is to obtain the geomorphological features of Phobos and Deimos. The spatial resolution of TENGOO is 0.3 m at an altitude of 25 km in the quasi-satellite orbit. The scientific objective of OROCHI is to obtain material distribution using spectral mapping. OROCHI possesses seven wide-angle bandpass imagers without a filter wheel and one monochromatic imager dedicated to the observation during the landing phase. Using these two instruments, we plan to select landing sites and obtain information that supports the analysis of return samples.

Keywords: MMX, TENGOO, OROCHI, Imager, Phobos, Deimos, Mars



Graphical abstract

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FULL PAPER Open Access

MMX geodesy investigations: science requirements and observation strategy

Koji Matsumoto*, Naru Hirata, Hitoshi Ikeda, Toru Kouyama, Hiroki Senshu, Keiko Yamamoto, Hirotomo Noda, Hideaki Miyamoto, Akito Araya, Hiroshi Araki, Shunichi Kamata, Nicola Baresi and Noriyuki Namiki

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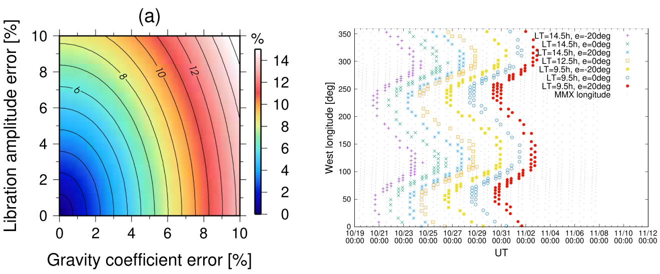
Abstract

In order to investigate the origin of Phobos and Deimos, the Japanese Martian Moons eXploration (MMX) mission is scheduled for launch in 2024. MMX will make comprehensive remote-sensing measurements of both moons and return regolith samples from Phobos to Earth. Geodetic measurements of gravity, shape, and rotation parameter of a body provides constraints on its internal structure reflecting its origin and evolution. Moments of inertia are important parameters to constrain the internal mass distribution, but they have not been well determined for the Martian moons yet. We discuss the mission requirements related to the moments of inertia to detect a potential heterogeneity of the mass distribution inside Phobos. We introduce mission instruments and operational strategies to meet the mission requirements. We present a preliminary imaging strategy from a quasi-satellite orbit for a base shape model that is expected to be created at the early stage of the mission. Geodetic products including ephemeris, gravity field, rotation parameter of Phobos, and spacecraft orbit are of importance not only for the geodetic study, but also for interpreting data from various mission instruments and selecting possible landing sites.

Keywords: MMX, Gravity, Shape, Rotation, Internal structure



Graphical abstract

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FULL PAPER Open Access

Science operation plan of Phobos and Deimos from the MMX spacecraft

Tomoki Nakamura*, Hitoshi Ikeda, Toru Kouyama, Hiromu Nakagawa, Hiroki Kusano, Hiroki Senshu, Shingo Kameda, Koji Matsumoto, Ferran Gonzalez-Franquesa, Naoya Ozaki, Yosuke Takeo, Nicola Baresi, Yusuke Oki, David J. Lawrence, Nancy L. Chabot, Patrick N. Peplowski, Maria Antonietta Barucci, Eric Sawyer, Shoichiro Yokota, Naoki Terada, Stephan Ulamec, Patrick Michel, Masanori Kobayashi, Sho Sasaki, Naru Hirata, Koji Wada, Hideaki Miyamoto, Takeshi Imamura, Naoko Ogawa, Kazunori Ogawa, Takahiro Iwata, Takane Imada, Hisashi Otake, Elisabet Canalias, Laurence Lorda, Simon Tardivel, Stéphane Mary, Makoto Kunugi, Seiji Mitsuhashi, Alain Doressoundiram, Frédéric Merlin, Sonia Fornasier, Jean-Michel Reess, Pernelle Bernardi, Shigeru Imai, Yasuyuki Ito, Hatsumi Ishida, Kiyoshi Kuramoto and Yasuhiro Kawakatsu

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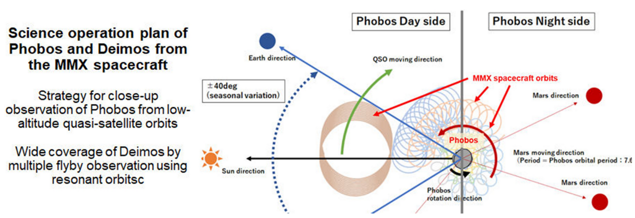
Abstract

The science operations of the spacecraft and remote sensing instruments for the Martian Moon eXploration (MMX) mission are discussed by the mission operation working team. In this paper, we describe the Phobos observations during the first 1.5 years of the spacecraft's stay around Mars, and the Deimos observations before leaving the Martian system. In the Phobos observation, the spacecraft will be placed in low-altitude quasi-satellite orbits on the equatorial plane of Phobos and will make high-resolution topographic and spectroscopic observations of the Phobos surface from five different altitudes orbits. The spacecraft will also attempt to observe polar regions of Phobos from a three-dimensional quasi-satellite orbit moving out of the equatorial plane of Phobos. From these observations, we will constrain the origin of Phobos and Deimos and select places for landing site candidates for sample collection. For the Deimos observations, the spacecraft will be injected into two resonant orbits and will perform many flybys to observe the surface of Deimos over as large an area as possible.

Keywords: MMX mission, Phobos, Deimos, QSO, Flyby



Graphical abstract

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FULL PAPER **Open Access**

In situ science on Phobos with the Raman spectrometer for MMX (RAX): preliminary design and feasibility of Raman measurements

Yuichiro Cho*, Ute Böttger, Fernando Rull, Heinz-Wilhelm Hübers, Tomàs Belenguer, Anko Börner, Maximilian Buder, Yuri Bunduki, Enrico Dietz, Till Hagelschuer, Shingo Kameda, Emanuel Kopp, Matthias Lieder, Guillermo Lopez-Reyes, Andoni Gaizka Moral Inza, Shoki Mori, Jo Akino Ogura, Carsten Paproth, Carlos Perez Canora, Martin Pertenais, Gisbert Peter, Olga Prieto-Ballesteros, Steve Rockstein, Selene Rodd-Routley, Pablo Rodriguez Perez, Conor Ryan, Pilar Santamaria, Thomas Säuberlich, Friedrich Schrandt, Susanne Schröder, Claudia Stangarone, Stephan Ulamec, Tomohiro Usui, Iris Weber, Karsten Westerdorff and Koki Yumoto

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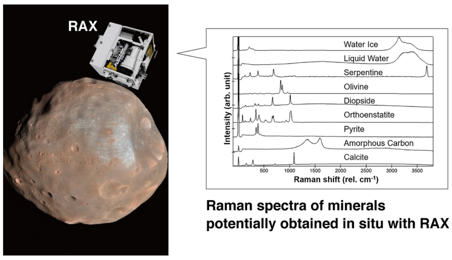
Abstract

Mineralogy is the key to understanding the origin of Phobos and its position in the evolution of the Solar System. In situ Raman spectroscopy on Phobos is an important tool to achieve the scientific objectives of the Martian Moons eXploration (MMX) mission, and maximize the scientific merit of the sample return by characterizing the mineral composition and heterogeneity of the surface of Phobos. Conducting in situ Raman spectroscopy in the harsh environment of Phobos requires a very sensitive, compact, lightweight, and robust instrument that can be carried by the compact MMX rover. In this context, the Raman spectrometer for MMX (i.e., RAX) is currently under development via international collaboration between teams from Japan, Germany, and Spain. To demonstrate the capability of a compact Raman system such as RAX, we built an instrument that reproduces the optical performance of the flight model using commercial off-the-shelf parts. Using this performance model, we measured mineral samples relevant to Phobos and Mars, such as anhydrous silicates, carbonates, and hydrous minerals. Our measurements indicate that such minerals can be accurately identified using a RAX-like Raman spectrometer. We demonstrated a spectral resolution of approximately 10 cm^{-1}, high enough to resolve the strongest olivine Raman bands at ~820 and ~850 cm^{-1}, with highly sensitive Raman peak measurements (e.g., signal-to-noise ratios up to 100). These results strongly suggest that the RAX instrument will be capable of determining the minerals expected on the surface of Phobos, adding valuable information to address the question of the moon's origin, heterogeneity, and circum-Mars material transport.

Keywords: Raman spectroscopy, Raman spectrometer for MMX (RAX), Phobos, Mineralogy, In situ analysis, Sample return, Martian Moons eXploration (MMX)



Graphical abstract

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FULL PAPER **Open Access**

The Mars system revealed by the Martian Moons eXploration mission

Kazunori Ogohara*, Hiromu Nakagawa, Shohei Aoki, Toru Kouyama, Tomohiro Usui, Naoki Terada, Takeshi Imamura, Franck Montmessin, David Brain, Alain Doressoundiram, Thomas Gautier, Takuya Hara, Yuki Harada, Hitoshi Ikeda, Mizuho Koike, François Leblanc, Ramses Ramirez, Eric Sawyer, Kanako Seki, Aymeric Spiga, Ann Carine Vandaele, Shoichiro Yokota, Antonella Barucci and Shingo Kameda

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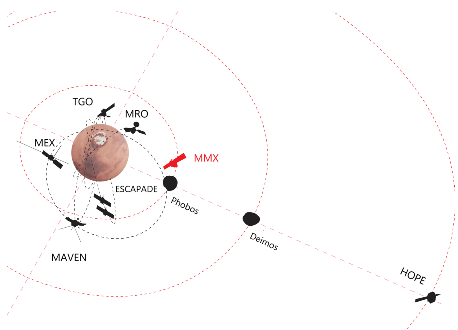
Abstract

Japan Aerospace Exploration Agency (JAXA) plans a Phobos sample return mission (MMX: Martian Moons eXploration). In this study, we review the related works on the past climate of Mars, its evolution, and the present climate and weather to describe the scientific goals and strategies of the MMX mission regarding the evolution of the Martian surface environment. The MMX spacecraft will retrieve and return a sample of Phobos regolith back to Earth in 2029. Mars ejecta are expected to be accumulated on the surface of Phobos without being much shocked. Samples from Phobos probably contain all types of Martian rock from sedimentary to igneous covering all geological eras if ejecta from Mars could be accumulated on the Phobos surface. Therefore, the history of the surface environment of Mars can be restored by analyzing the returned samples. Remote sensing of the Martian atmosphere and monitoring ions escaping to space while the spacecraft is orbiting Mars in the equatorial orbit are also planned. The camera with multi-wavelength filters and the infrared spectrometer onboard the spacecraft can monitor rapid transport processes of water vapor, dust, ice clouds, and other species, which could not be traced by the previous satellites on the sun-synchronous polar orbit. Such time-resolved pictures of the atmospheric phenomena should be an important clue to understand both the processes of water exchange between the surface/underground reservoirs and the atmosphere and the drivers of efficient material transport to the upper atmosphere. The mass spectrometer with unprecedented mass resolution can observe ions escaping to space and monitor the atmospheric escape which has made the past Mars to evolve towards the cold and dry surface environment we know today. Together with the above two instruments, it can potentially reveal what kinds of atmospheric events can transport tracers (e.g., H_2O) upward and enhance the atmospheric escape.

Keywords: Mars, Mars system, Paleoclimate, Atmospheric escape, Water cycle, Dust cycle, Transport process



Graphical abstract

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The MMX rover: performing in situ surface investigations on Phobos

Patrick Michel*, Stephan Ulamec, Ute Böttger, Matthias Grott, Naomi Murdoch, Pierre Vernazza, Cecily Sunday, Yun Zhang, Rudy Valette, Romain Castellani, Jens Biele, Simon Tardivel, Olivier Groussin, Laurent Jorda, Jörg Knollenberg, Jan Thimo Grundmann, Denis Arrat, Gabriel Pont, Stephane Mary, Markus Grebenstein, Hirdy Miyamoto, Tomoki Nakamura, Koji Wada, Kent Yoshikawa and Kiyoshi Kuramoto

Earth, Planets and Space 2022, **74**:2 DOI: 10.1186/s40623-021-01464-7
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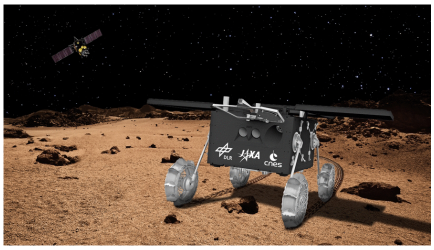
Abstract
The Japanese MMX sample return mission to Phobos by JAXA will carry a rover developed by CNES and DLR that will be deployed on Phobos to perform in situ analysis of the Martian moon's surface properties. Past images of the surface of Phobos show that it is covered by a layer of regolith. However, the mechanical and compositional properties of this regolith are poorly constrained. In particular, from current remote images, very little is known regarding the particle sizes, their chemical composition, the packing density of the regolith as well as other parameters such as friction and cohesion that influence surface dynamics. Understanding the properties and dynamics of the regolith in the low-gravity environment of Phobos is important to trace back its history and surface evolution. Moreover, this information is also important to support the interpretation of data obtained by instruments onboard the main MMX spacecraft, and to minimize the risks involved in the spacecraft sampling operations. The instruments onboard the Rover are a Raman spectrometer (RAX), an infrared radiometer (miniRad), two forward-looking cameras for navigation and science purposes (NavCams), and two cameras observing the interactions of regolith and the rover wheels (WheelCams). The Rover will be deployed before the MMX spacecraft samples Phobos' surface and will be the first rover to drive on the surface of a Martian moon and in a very low gravity environment.

Keywords: Camera, Numerical modelling, Phobos, Radiometer, Raman spectrometer, Regolith, Regolith dynamics, Thermal inertia, Rover



Graphical abstract

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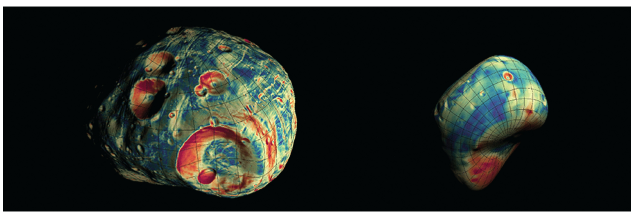
High-resolution shape models of Phobos and Deimos from stereophotoclinometry

Carolyn M. Ernst*, R. Terik Daly, Robert W. Gaskell, Olivier S. Barnouin, Hari Nair, Benjamin A. Hyatt, Manar M. Al Asad and Kielan K. W. Hoch

Earth, Planets and Space 2023, **75**:103 DOI: 10.1186/s40623-023-01814-7
Received: 28 January 2021, Accepted: 6 April 2023, Published: 25 June 2023

Abstract
We created high-resolution shape models of Phobos and Deimos using stereophotoclinometry and united images from Viking Orbiter, Phobos 2, Mars Global Surveyor, Mars Express, and Mars Reconnaissance Orbiter into a single coregistered collection. The best-fit ellipsoid to the Phobos model has radii of (12.95 ± 0.04) km × (11.30 ± 0.04) km × (9.16 ± 0.03) km, with an average radius of (11.08 ± 0.04) km. The best-fit ellipsoid to the Deimos model has radii of (8.04 ± 0.08) km × (5.89 ± 0.06) km × (5.11 ± 0.05) km with an average radius of (6.27 ± 0.07) km. The new shape models offer substantial improvements in resolution over existing shape models, while remaining globally consistent with them. The Phobos model resolves grooves, craters, and other surface features ~ 100 m in size across the entire surface. The Deimos model is the first to resolve geological surface features. These models, associated data products, and a searchable, coregistered collection of images across six spacecraft are publicly available in the Small Body Mapping Tool, and will be archived with the NASA Planetary Data System. These products enable an array of future studies to advance the understanding of Phobos and Deimos, facilitate coregistration of other past and future datasets, and set the stage for planning and operating future missions to the moons, including the upcoming Martian Moons eXploration (MMX) mission.

Keywords: Phobos, Deimos, Martian moons, Small bodies, Shape, Topography, Stereophotoclinometry, Martian Moons eXploration



Graphical abstract

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Earth, Planets and Space

TECHNICAL REPORT Open Access

Light detection and ranging (LIDAR) laser altimeter for the Martian Moons Exploration (MMX) spacecraft

Hiroki Senshu*, Takahide Mizuno, Kazuhiro Umetani, Toru Nakura, Akihiro Konishi, Akihiko Ogawa, Hirokazu Ikeda, Koji Matsumoto, Hirotomo Noda, Yoshiaki Ishihara, Sho Sasaki, Naoki Tateno, Yasuyuki Ikuse, Katsunori Mayuzumi, Teiji Kase and Hisayoshi Kashine

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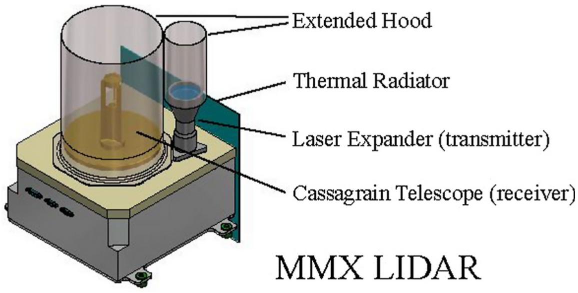
Received: 15 January 2021, Accepted: 24 October 2021, Published: 14 December 2021

Abstract

An altimeter is a critical instrument in planetary missions, for both safe operations and science activities. We present required specifications and link budget calculations for light detection and ranging (LIDAR) onboard the Martian Moons Exploration (MMX) spacecraft. During the mission phase, this LIDAR will continuously measure the distance between the spacecraft and its target. The time-series distance provides important diagnostic information for safe spacecraft operations and important information for geomorphological studies. Because MMX is a sample return mission, its LIDAR must accommodate physical disturbances on the Martian satellite surface. This resulted in changes to the optical system design.

Keywords: LIDAR, MMX, Phobos



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Continued from back cover

Science operation plan of Phobos and Deimos from the MMX spacecraft
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