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Spacecraft exploration of Phobos and Deimos

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ABSTRACT

We review the previous exploration of Phobos and Deimos by spacecraft. The first close-up images of Phobos and Deimos were obtained by the Mariner 9 spacecraft in 1971, followed by much image data from the two Viking orbiters at the end of the 70s, which formed the basis for early Phobos and Deimos shape and dynamic models. The Soviet Phobos 2 spacecraft came within 100 km of landing on Phobos in 1988. Mars Global Surveyor (1996–2006) and Mars Reconnaissance Orbiter (since 2005) made close-up observations of Phobos on several occasions. Mars Express (since 2003) in its highly elliptical orbit is currently the only spacecraft to make regular Phobos encounters and has returned large volumes of science data for this satellite. Landers and rovers on the ground (Viking Landers, Mars Pathfinder, MER rovers, MSL rover) frequently made observations of Phobos, Deimos and their transits across the solar disk.

1. Introduction

It was nearly 90 years after the discovery of Phobos and Deimos by Asaph Hall in 1877 at the US Naval Observatory before spacecraft were sent to Mars to explore the red planet and its moons. This section describes the many spacecraft sent to Mars that observed Phobos and Deimos and the data sets that they produced that will keep researchers busy for decades trying to answer the most basic questions of origin, evolution and current states.

The fleet of spacecraft that have observed the two Martian moons include:

- Mars flyby missions:
  - NASA Mariners 4, 5 and 6
  - ESA Rosetta (still operating)
- Mars orbiter missions:
  - NASA Mariner 9
  - Viking Orbiters 1 and 2
  - Soviet Phobos 88
  - NASA Mars Global Surveyor
  - NASA Mars Odyssey Orbiter (still operating)
  - ESA Mars Express (still operating)
  - NASA Mars Reconnaissance Orbiter (still operating)
- Mars lander/rover missions:
  - Viking Landers 1 and 2
  - Mars Pathfinder
  - Mars Exploration Rover Spirit and Opportunity (still operating)
  - Mars Surface Laboratory Curiosity (still operating)

NASA spacecraft data for Phobos are available from the Planetary Data System (PDS) [1] and the National Space Science Data Center (NSSDC) [2]. Data from European Space Agency (ESA) missions can be found at [3]. Ancillary data such as trajectory, ephemerides, spacecraft attitude and clock, instrument pointing and models, etc. are available at [4]. Sample images of Phobos and Deimos taken by different missions and instruments can be found at [5] and [6].

2. Mariners 4, 6 and 7

NASA's Mariners 4, launched in 1965, and 6 and 7, launched in 1969, were Mars flyby missions. The objectives of these missions were focused on Mars with no goals to observe Phobos and Deimos. The Mariner 4 vidicon camera, with a $1.05^\circ \times 1.05^\circ$ field of view, obtained 21 Mars images that can be found at [7]. Other related Mariner 4 publications are: Nicks (1967), Sloan (1968), Anderson (1965), and NASA (1967).

In 1969, Mariner 6 and Mariner 7 completed the first dual mission to Mars, flying by over the equator and south polar regions and analyzing the Martian atmosphere and surface with remote sensors, as well as recording and relaying hundreds of

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pictures. By chance, both flew over cratered regions and missed seeing the giant northern volcanoes and the equatorial grand canyon that was discovered later. The two spacecraft each carried the Mars Wide and Narrow Angle TV Cameras, the IR Spectrometer, the Two-Channel IR Radiometer, the UV Spectrometer, the Thermal Control Flux Monitor and the Celestial Mechanics/Relativity Experiments.

It is expected that Phobos and Deimos were captured by Mariners 6 and 7 during the approach to Mars as point source images off of the Mars limb or possibly with Phobos in transit across Mars. However, the Mars approach and flyby images were not archived so one cannot go back and search for these point source images. Such observations would have extended the time span of spacecraft observations by two years, very important in determining the orbits, including secular accelerations/deceleration of the Martian moons. Publications giving more information on Mariners 6 and 7 include: Collins (1971) and NASA (1969).

3. Mariner 9

In 1971, Mariner 9 became the first spacecraft to orbit another planet. It carried an Infrared Radiometer (IRR), an Ultraviolet Spectrometer (UVS), an Infrared Interferometer Spectrometer (IRIS), a Television System and a Celestial Mechanics/S-Band Occultation Experiments. The objectives of these experiments were to analyze the surface and atmosphere of Mars. However bonus science was obtained when these instruments were able to view the Martian moons during close flybys.

Mariner 9 was able to map 85% of the Martian surface at a resolution of 1–2 km (with 2% mapped at a resolution of 100–300 m) in addition to gathering abundant information about the surface and atmosphere. Mariner 9 carried a wide-angle camera having a $11^\circ \times 14^\circ$ field of view for systematic mapping of Mars and a narrow angle camera having a $1.1^\circ \times 1.4^\circ$ field of view for viewing local Martian features. Seven thousand three hundred twenty nine images were taken, included the first detailed views of Olympus Mons, the solar system's largest volcano; Valles Marineris, a vast canyon system that dwarfs the Grand Canyon and was named for this spacecraft; the polar caps; and the moons Phobos and Deimos.

The Martian moons were imaged on Mars approach, against star fields, as a technical flight demonstration of a new technique for interplanetary navigation. The demonstration exceeded expectations and optical navigation has been included on many follow-on Mars, outer planet, comet and asteroid missions. Once in Mars orbit, the highly elliptic and large Mariner 9 orbit that went outside of the Deimos orbit would periodically fly near the Martian moons where images were taken anytime the range was less than 7000 km. Images as close as 1200 km were taken where a narrow angle pixel covered about 30 m.

A total of 214 images of Phobos and Deimos were obtained in greyscale from the narrow angle camera and in color using the red, green and blue filters of the wide-angle camera. These images were the first to resolve the global shapes and surface topographies showing the two Martian moons to be highly irregularly shaped and regolith-covered surface saturated with craters. The images showed Phobos and Deimos to be in synchronous rotation with Phobos having a forced rotational libration amplitude at the 1° level. A controlled drawing of the Phobos surface features was the first cartographic map of a moon of another planet with some craters given names by the IAU Nomenclature Committee. The orbital speeds of Phobos and Deimos confirmed that Phobos was speeding up as it was spiraling in toward Mars while Deimos was spiraling away from Mars due to tidal forces raised by the moons on Mars. Hints of crater chains were seen that were later resolved by Viking orbiter images to be part of the global groove network.

A summary of the entire Mariner 9 image archive, including the Phobos and Deimos images, is given by Cutts, 1974. The atlas contains a description of each image plus a thumbnail image. Digital versions of Mariner 9 images are available from the PDS at [8]. The entire image collection is also archived in photographic and digital formats at the NASA GSFC NSSDC [9].

Other websites hosting Mariner 9 data include:

UVS Data Files, Mariner Mars 1971 (MM71/M9) Ultraviolet Spectrometer (UVS) Data [10]
Experimenter Data Records files: [11]
Supplemental Experimenter Data Record files: [12]
General descriptions are at [13].

Additional information on the project and images can be found in: Steinbacher et al. (1972), Hartmann and Raper (1974), Steinbacher and Haynes (1973), Cutts (1974), Duxbury et al. (1974), Pollack et al. (1972,1973), Gatley et al. (1974), Simmons and Hendrix (1999), and Pang et al. (1987).

4. Viking orbiters/landers

The Viking project placed two spacecraft into Mars orbit and two landers on the Martian surface in 1976. Both orbiters carried Imaging Systems, Infrared Thermal Mappers (IRTM), Mars Atmospheric Water Detectors (MAWD) and Radio Science experiments, all of which observed Phobos and Deimos during close flybys. The Lander Stereo Cameras viewed Phobos and Deimos from the surface of Mars. The Viking project elevated Phobos and Deimos exploration as a high science objective during its extended mission phase and targeted many close flybys of the Mars moons. Additionally, the shadow of Phobos passing over Viking Lander 1 was observed simultaneously three times from the lander and Viking Orbiter 1. The Viking orbiter/lander datasets stood as the most exhaustive data on the Martian moons for almost 40 years, only recently being exceeded by the ESA Mars Express mission.

Viking had many new discoveries related to Phobos and Deimos:

The global network of grooves;

Complete global coverage of the entire surfaces with significant coverage in color, UV and IR;

The first digital terrain model (DTM) of another planet's moon (Phobos) and the first global image mosaic (also Phobos);

The first mass determinations of the two moons showing that they were anomalous to Mars and asteroids by having densities of less than 2 g/cm^3;

Phobos and Deimos surfaces were covered by fine-grained regoliths, tens of meters or thicker; and

Phobos had a forced rotational libration of about 1° amplitude and that this amplitude was consistent with Phobos having a homogeneous interior (low density material or loosely compacted Mars primordial disk material or crater ejecta), covered by regolith.

All Viking Orbiter and Lander data of Phobos and Deimos are archived at NASA's PDS and NSSDC facilities: [14] (Viking Orbiter) and [15] (Viking Lander).

A photo journal of the close flyby images of Phobos is given in Duxbury et al. (1984). A detailed report of the IR results can be found in Lunine et al. (1982).

5. Phobos 88

The Soviet Phobos 2 spacecraft went into Mars orbit in 1988 for three months and came within 100 km of landing on Phobos. Phobos 2 carried many orbiter and lander instrument. The orbiting remote sensing instruments that observed Phobos and Deimos included: the Automatic Space Plasma Experiment with Rotating Analyzer (ASPERA), the Videospectrometric System (VSK), the Infrared Mapping Spectrometer (ISM), the Infrared Radiometer/Spectrometer (KFRM), and the Scanning Infrared Radiometer (Termoscan).

The VSK included two wide-angle cameras (red and blue channels) and a high-resolution narrow-angle camera to yield visual and color images of Phobos. VSK also captured Deimos as a point source with Jupiter and the bright star Aldebaran.

The science and associated ancillary engineering data were archived by the Soviet Academy of Sciences Space Research Institute (IKI) and the NASA Planetary Data System (PDS) and NASA Ancillary Information Facility (NAIF) under the US/Soviet Joint Working Group for Solar System Exploration.

The ISM data archive is at [16]. The KRFM, Termoscan, and VSK data are available at [17]. The ancillary engineering data are archived as NAIF SPICE kernels at [18].

Data returned from the Phobos-1 and -2 missions

Experiment characteristics	Available data	References
Video spectrometric system (VSK) Fregat	37 TV images of Phobos (and Phobos against Mars) from distance of 190–1100 km	Avanesov et al. (1989)
Multichannel instrument KRFM	Phobos observation from a height of 190 km on 25.03.1989	Ksanfomality et al. (1989)
– Radiometer 6–50 μm	Observation period 420 s	
– Photometer 320–600 nm	Relative speed 43 m/s 1st track at the surface Latitude: -4.5° Longitude: 140–260° West	
Thermal and special properties of the Phobos regolith	2nd track Latitude: 2.7° Longitude: 196–229° West	
Imaging spectrometer ISM	Mars observation:	Bibring et al. (1989)
– 1.65–3.16 μm and – 0.76–1.54 μm	From <2000 km	
Surface mineralogy of Mars and Phobos, composition of the Martian atmosphere	40,000 spectra of Mars and Phobos	
Themoscan, thermal imaging of the surface of Mars Radiometer • 8.5–12 μm and • 0.5–0.95 μm	The first session of measurement – on 11.02.1989 (intermediate elliptical orbit, altitude during observation 1150–5200 km, resolution ~300 m) The second session of measurement – on 01.03.1989 (circular orbit, altitude 6300 km)	Selivanov et al. (1989)
Gamma-ray Spectrometer 100×100 mm^2 CsI (Tl) crystal 0.3–10.0 MeV Elemental composition of the Martian soil	Measurements of γ-radiation from Mars during passing the perigee at the first four elliptical orbits, the altitude of the perigee ~870 km (1, 5, 8 and 11 February 1989).	Surkov et al. (1989)
APEX experiment Temporal variations and spectral characteristics of cosmic γ-ray emissions, γ-ray albedo of the Martian surface. Range – 60 keV–9 MeV 100×100 mm^2 CsI(Tl) crystal	Measurements of γ-radiation from Mars during passing the perigee at the first four elliptical orbits, the altitude of the perigee ~870 km (1, 5, 8 and 11 February 1989).	d' Uston et al. (1989)
Solar occultation experiment	32 occultations in the period between 08.02.1989 and 17.02.1989	Blamont et al. (1989), Krasnopolsky et al. (1989)
Vertical profile of the Martian atmosphere – Spectrograph: spectral range 215–328 nm (512 elements) – Fabry-Perot interferometer 760 nm (Δ 0.2 nm, 80 elements) and 936 nm (Δ 0.3 nm, 80 elements) – Grating spectrograph (5290–5370 cm^{-2} 2707–2740 cm^{-2} 24 elements each)		
MAGMA (magnetic fields near Mars) and FGMM (flux-gate magnetometer Mars) Range of both magnetometers +/−100 nT	Measurements of the magnetic field during operation of the spacecraft at the elliptical and the circular orbits around Mars	Riedler et al. (1989)
PWS, plasma wave system Two sensors: dipole antenna and Langmuir probe	Measurements of the electromagnetic and electrostatic waves during operation of the spacecraft at the elliptical and the circular orbits around Mars	Grad et al. (1989)

ASPERA, automatic space plasma experiment with a rotation analyzer	Measurements of the energy spectra of ions and electrons and their angular distribution during operation of the spacecraft at the elliptical and the circular orbits around Mars	Lundin et al. (1989)
Measurements energy, and angular distribution of ions of charge e with energies 0.5 eV e^{-1}–24 keV e^{-1} and electrons with energies 1 eV–50 keV		
TAUS experiment	Measurements of the energy spectra of ions during operation of the spacecraft at the elliptical and the circular orbits around Mars	Rosenbauer et al. (1989)
Ions (H^+, He^+ and "heavy ions") distribution and dynamics in the Martian environment		
Energy range 30 V–6 kV		
HARP spectrometer.	Measurements of the energy spectra of ions during operation of the spacecraft at the elliptical and the circular orbits around Mars	Shutte et al. (1989)
Hyperbolic analyzer in the retarding potential mode		
Energy range 0.2–800 eV		
SLED	Measurements of the energetic electrons and ions during operation of the spacecraft during the cruise phase and at the elliptical and the circular orbits around Mars	Afonin et al. (1989), McKenna-Lawlor et al. (1991)
Energy spectra of charge particles in the energy range from 30 keV to a few MeV		
LET, low energy telescope	Measurements during the 9-months interval from July 1988 to March 1989	Marsden et al. (1991)
Spectra range 1–75 MeV		
LILAS	Measurements in the period from July 1988 to March 1989	Barat et al. (1991)
Investigation of cosmic gamma-rays bursts in the range 3–1000 keV	Recorded 72 cosmic rays bursts during 200 effective days of operations	
RF-15, broadband photometry of the solar soft X-rays 294 and 4–8 keV	Measurements in the period between 14.07.1988 and 17.03.1989	Valnicek et al. (1991a)
SUFR, solar ultraviolet radiometer	Measurements on 8–11 March and 23 March 1989	Kazachevskaya et al. (1991)
Record solar emission flux at $\lambda < 130$ nm		
IPHIR – three-channel sun-photometer (SPM) – 335, 500 and 862 nm – two-axis solar sensor (TASS) – data processing unit	24 measurements	Bruns and Shumoko (1991), Bruns et al. (1990)
TEREK experiment, Onboard the Phobos-1 spacecraft.	Observations: 23.07.1988	Valnicek et al. (1991b)
Imaging of the whole solar disk in X (0.5–2.5 nm), E.U.V. (17–18, 30.4 nm) and optical coronograph (400–600 nm)	26.07.1988 27.07.1988 Altogether 448 images were received	
Celestial mechanic experiment	Measurements during orbiting around Mars	Kolyuka et al. (1991)
Ground based measurements		

6. Mars pathfinder

The 1996 Mars Pathfinder Rover made multispectral measurements of both Phobos and Deimos from the surface of Mars using its Imager for Mars Pathfinder (IMP) camera (Thomas et al., 1999; Murchie et al., 1999). Mars Pathfinder image data are available from the PDS at [19].

7. MGS

The Mars Global Surveyor (MGS) spacecraft went into Mars orbit in 1997 and performed flawlessly for 10 years. Its scientific remote sensing payload that observed Phobos, Deimos and the shadow of Phobos included: the Mars Orbiter Camera (MOC), the Thermal Emission Spectrometer (TES), and the Mars Orbiter Later Altimeter (MOLA). MGS was a polar orbiter flying about 400 km above Mars giving no opportunity for any close flybys of the Martian moons during this mission phase. However as MGS initially went into Mars orbit and was using aerobraking to obtain the low circular orbit, close flybys of Phobos were targeted and MOC, TES, and MOLA data were obtained from Phobos. Once in the low, circular orbit, a few images of Deimos and the shadow of Phobos were taken (Bills et al., 2005). MSSS MOC images of Phobos, Deimos and shadows (Fig. 1) can be found at [20] or [21]. Other MGS data including TES and MOLA data are archived at [22].

8. Odyssey

The Mars 2001 Odyssey spacecraft went into a low, circular Mars orbit in October 2001 and did not observe Phobos or Deimos. However, the Thermal Emission Imaging System camera (THEMIS) observed the shadow of Phobos in February 2012. The Mars 2001 Odyssey orbiting spacecraft is still operating.

9. MRO

The Mars Reconnaissance Orbiter went into its low, near-circular orbit in August 2006. During approach, Phobos and Deimos were observed as point sources against star fields by the Navigation Camera. This camera had a 500 mm focal length, 12 μm × 12 μm pixels in a 1020 × 1024 CCD. Over 500 Deimos star images and over 100 Phobos

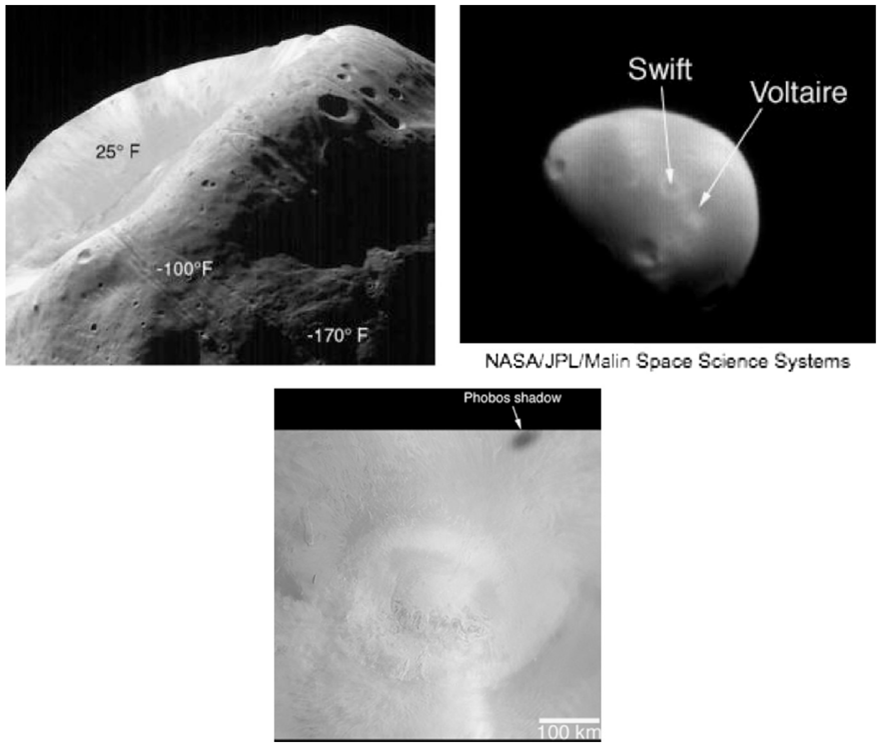

Fig. 1. NASA MSSS MOC images of the Phobos (upper left) with temperatures from TES, Deimos (upper right) and the Phobos shadow (bottom).

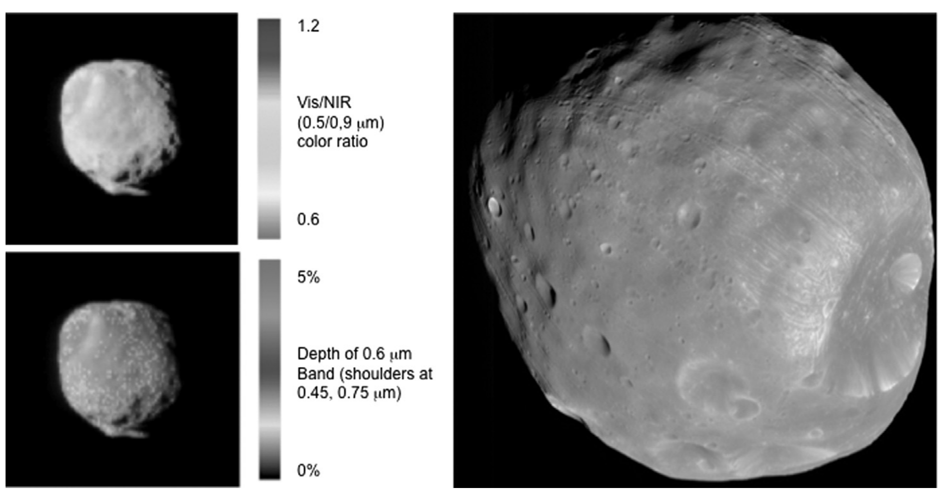

Fig. 2. NASA MRO APL CRISM and University of Arizona HiRISE images of Phobos.

star images were taken. Reduced astrometric data can be located at [23] and had positional accuracies at the km level.

While in orbit, MRO occasionally imaged Phobos (Fig. 2) and Deimos with its High Resolution Imaging Science Experiment (HiRISE) and the hyper-spectral infrared Compact Reconnaissance Imaging Spectrometer for Mars (CRISM). The NASA MRO orbiting spacecraft is still operating and expected to periodically add new observations of Phobos and Deimos. The HiRISE observations are described in Thomas et al. (2010) and can be found at [24]. The CRISM observations are described in Murchie et al. (2008). CRISM data are archived by the PDS at [25].

10. MER rovers

Multiple images of Phobos and Deimos transits across the sun (Fig. 3) were taken by the two MER Rovers, Spirit and Opportunity, and continue to be taken by Opportunity using the Pancam system [26]. The complete archive of MER images within the PDS at [27] and [28], also see [29].

11. MEX

Chapter XI is entirely devoted to the ESA Mars Express Exploration of Phobos and Deimos. A short history of this exploration is included here for completeness of this chapter so that it can stand alone. The European Mars Express mission arrived at Mars on 25 December 2003. Unfortunately, the lander Beagle 2 was lost after atmospheric entry and descent. The core of the mission, however, the Mars Express orbiter was inserted successfully in an elliptical orbit around Mars having an inclination of 86.6°. With a period of 7.6 h, a periapsis height of about 260 km and a semi-major axis close to 9300 km, Mars Express is routinely going beyond Phobos′ orbit. Despite several orbit changes to adjust for scientific needs for Mars observations, the general characteristics of the Mars Express orbit remained similar. The satellite approaches Phobos about every 500 orbits at distances well below 1000 km (Fig. 4). With orbit number 11,453 on 31 December 2012, the Mars Express has completed its 3rd mission extension and continues successfully its scientific operations after nine years around Mars. The orbit now has a period of 7 h with its periapsis at 350 km and a semi-major axis of 8850 km. Mars Express performed small orbit phasing maneuvers since 2008 (after orbit 6000) to increase the number of very close flybys around 100 km to Phobos and below.

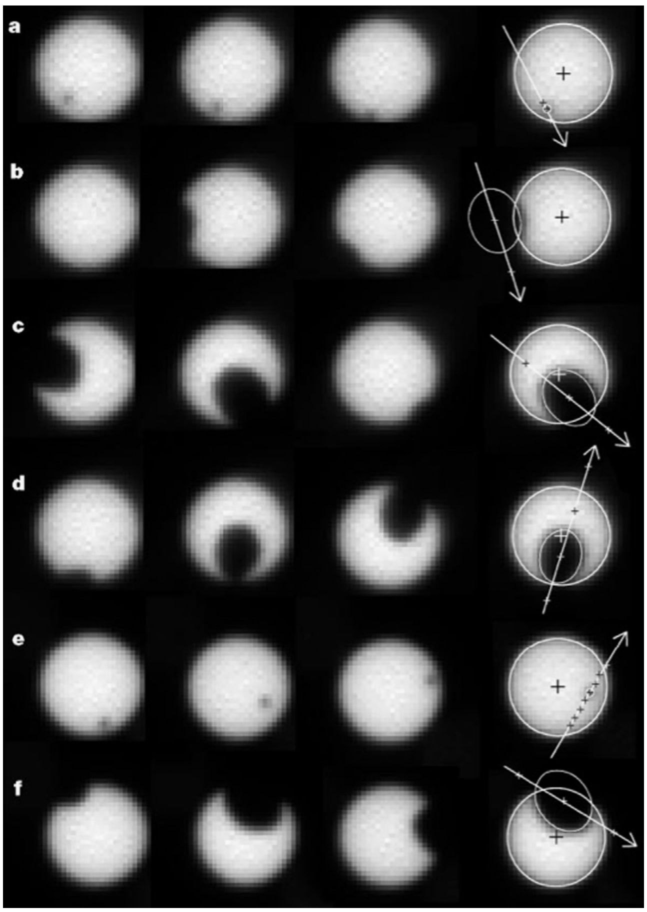

Fig. 3. MER rover images of Phobos and Deimos in transit across the sun.

Mars Express carries seven experiments with the High Resolution Stereo Camera (HRSC), the imaging spectrometer Observatoire pour la Minéralogie, l′Eau, les Glaces et l′Activité (OMEGA), the Planetary Fourier Spectrometer (PFS), the UV-IR spectrometer Spectroscopy for the Investigation of the Characteristics of the Atmosphere of Mars (SPICAM), the radar instrument Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS), the plasma package Analyzer of Space Plasmas and EneRgetic Atoms (ASPERA-3), and the Mars Radio Science experiment (MaRS). All instruments contributed to the Mars Express investigation of Phobos and a detailed summary of the observations and achievements is given in the accompanying paper by Witasse et al. (2013). In addition, Mars Express is equipped with a technical camera system, the Video Monitoring Camera (VMC), designed for the documentation of the lander release, which is used since 2008 for monitoring purposes and public outreach activities. All Mars Express observation data are and will be archived in ESA′s Planetary Science Archive (PSA) [30] and NASA′s Planetary Data System (PDS) [31].

OMEGA is an imaging spectrometer from 0.38–5.1 μm comprising three wavelength channels. In the visible, it is operated as a pushbroom scanner while in the near- and shortwave-infrared OMEGA works as a whiskbroom scanner. OMEGA used close flybys for Phobos observations to decipher its surface composition.

PFS is a point spectrometer from 1.2 μm to 45 μm optimized for atmospheric studies at Mars. With its FOV of 1.7° in the short wavelength range and of 2.8° in the long wavelength range, PFS acquires spectra of Phobos at distances well below 1000 km.

SPICAM is a dual spectrometer for investigations of the Martian atmosphere. It consists of an UV channel covering the wavelength range of 118–320 nm and a near-infrared channel from 1.0 μm to 1.7 μm. SPICAM performs Phobos measurements to better understand its composition mostly together with the HRSC camera and is operating also during far-distant observations.

MARSIS is an active sounding radar instrument operating in the wavelength range of 0.1–5.5 MHz. Its main interest with respect to

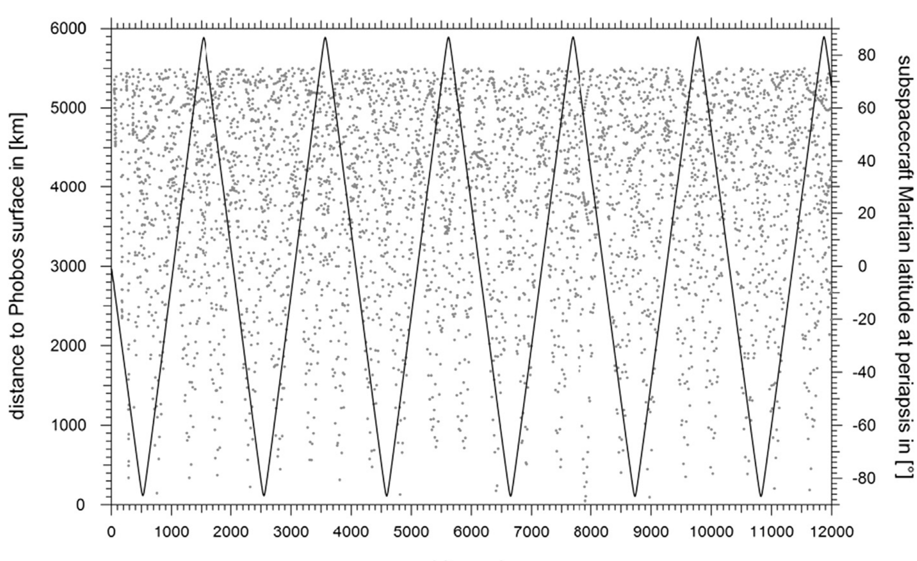

Fig. 4. Encounters of Mars Express with Phobos at distances to the surface below 5500 km (dots) compared with the latitudinal drift of the periapsis (solid line) since Mars Express orbit insertion.

Phobos is to decipher the internal structure of the Martian moon. Technical reasons constrain MARSIS observations to distances between about 100 km and 500 km.

MaRS makes use of the Mars Express communication system for radio science investigations around Mars including gravity, bistatic radar, ionospheric sounding and investigations of the solar corona during conjunctions. Measurements at Phobos are performed by pointing the antenna towards Earth and are aiming to better constrain its mass and internal structure. First results have demonstrated that very close flybys like those planned for the next years with flyby distances below 50 km are needed for further improvements.

ASPERA-3 finally comprises four different sensors to investigate the interactions of the solar wind with the Martian atmosphere and to investigate the plasma and neutral gas environment of Mars including the influence by the Martian moons. Measurements in the vicinity of Phobos have been performed whenever feasible.

The HRSC is a multiple-line single-optics pushbroom scanner with five panchromatic channels for nadir high-resolution (40 m/pixel at 1000 km distance) and quintuple stereo imaging as well as four multispectral channels for color imaging. An additional channel with separate optics and a frame detector, the Super Resolution Channel (SRC), yields a four times better spatial resolution. Since the end of 2012, HRSC was switched on in 3513 orbits and has acquired more than 39,000 images including 8474 SRC frames until now. One hundred ninety nine of these orbits were used by HRSC to acquire imaging sequences of Phobos. The pushbroom scanner was mainly applied to obtain stereo and/or color imagery at distances preferably $\leq$ 1500 km (Fig. 5). The SRC performed additional far-distant astrometric observations $\leq$ 5500 km together with the nadir channel. Achievements of the HRSC are discussed in several accompanying papers of this issue.

On 5 November 2009, Mars Express was pointed towards Phobos to obtain a video sequence with the SRC showing a Deimos occultation by Phobos (Fig. 6) that can be found at [32, 33, 34, 35]. A Jupiter occultation by Phobos was observed by SRC on 1 June 2011[36, 37]. The HRSC also observed the shadow of Phobos on the Martian surface in ten imaging sequences. Mars Express was specifically pointed off nadir to capture the passage of Phobos′ shadow on nine of the ten sequences. One image sequence occurred in normal nadir attitude. A similar search for detecting the penumbra of Deimos by HRSC was not successful.

The second Martian moon Deimos is well outside of the Mars Express orbit. The closest approach to Deimos during nominal mission was well above 9500 km. Observations are restricted to the Mars facing side and spatial resolutions $\leq$ 100 m/pixel are barely achieved by SRC. Main emphasis for investigating Deimos was given to refine its orbital parameters and to better constrain its surface composition. HRSC has obtained imaging sequences during 68 orbits with its nadir channel together with the SRC channel. SPICAM was operating together with HRSC for most of the Deimos observations. Rather recently, OMEGA has also

Fig. 6. SRC image of Phobos partial occultation of Deimos sequence.

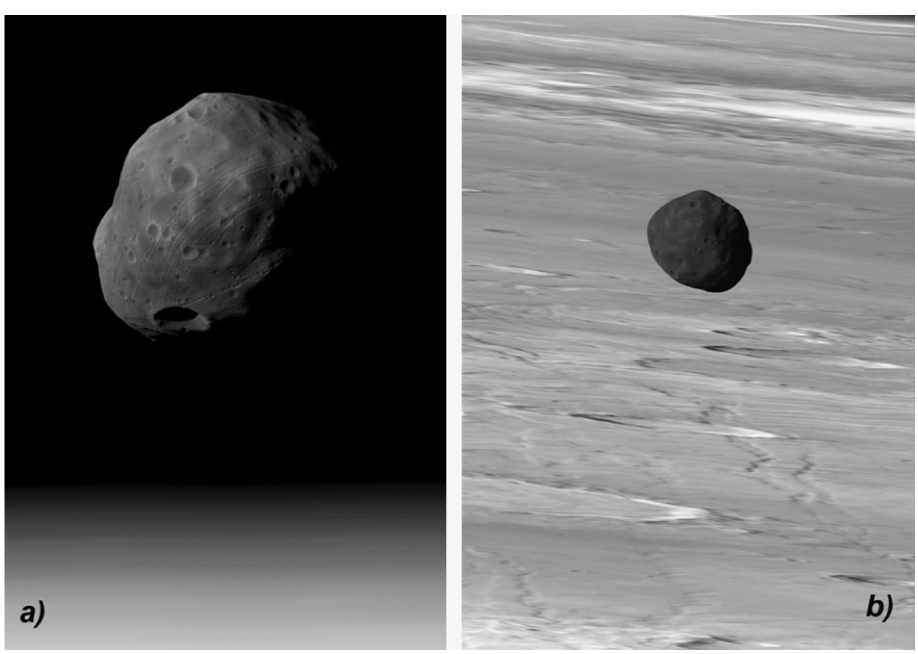

Fig. 5. Imaging by the HRSC pushbroom scanner: (a) Phobos above the Martian limb in orbit 6906 at 530 km distance with the P1 panchromatic channel. (b) Phobos above the Martian surface in orbit 7982 at a distance of 1382 km.

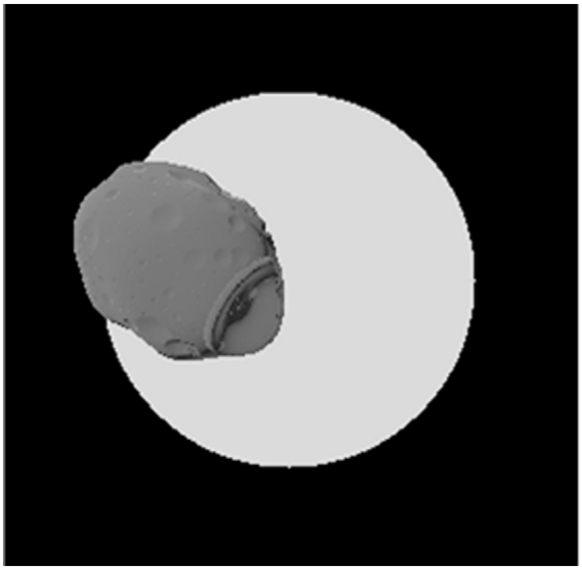

Fig. 7. Predicted solar transit by Phobos as viewed from MSL curiosity.

increased its number of Deimos observations with its visible channel.

Searches for rings and moons of Mars were carried out using both the HRSC Nadir and Super Resolution channels as the MEX spacecraft passed through the Mars equatorial plane on five different occasions. Image sequences were obtained at both low (backward scattered light) and high (forward scattered light) solar phase angles. To date, nothing has been observed; however additional attempts will be made using the experience gained from the existing sequences.

Mars Express data are archived within the ESA′s Planetary Science Archive (PSA) at [38] and with the PDS at [39]. The MEX observation of Phobos and Deimos will continue beyond what is reported here as the spacecraft is still active in its operations at Mars.

12. Rosetta

The ESA spacecraft Rosetta flew by Mars for a gravity assist before continuing its journey to a comet. On 24 February 2007 before closest approach, the Optical, Spectroscopic and Infrared Remote Imaging System (OSIRIS) observed Phobos and its shadow in transit of Mars. A video animation is available at [40]. More details about the OSIRIS NAC multispectral observations of Phobos before and after closest approach are described by Pajola et al. (2012).

13. MSL

MSL Curiosity is observing Phobos/Deimos solar transits (Fig. 7), mutual encounters and encounters with Jupiter and Saturn to support orbit evolution and Mars interior studies. MSL data can be found from the PDS at [41].

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