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Mars Science and Exploration After Mars Express

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Abstract

Mars Express (MEX) is one of the most productive planetary missions of the European Space Agency (ESA). This low cost (∼150 M€) mission has been instrumental in shaping the planetary community in Europe and has contributed to paving the way for many subsequent ESA endeavours. During more than two decades, Mars Express has collected a wealth of data in all disciplines of Martian science. This paper concludes the Topical Collection "Mars Express: Pioneering Two Decades of European Science and Exploration of Mars" prepared under the auspices of the International Space Science Institute. It briefly describes various aspects of the mission (leaving details to dedicated articles), summarizes the major science achievements, discusses the lessons learned from 20 years of Mars Express operations, and bridges with future Mars science and exploration.

Keywords Mars Express · Science highlights · Lessons learned · Future prospective

1 Introduction

Mars Express is one of the most successful and productive planetary missions of ESA. It was conceived as a European "resurrection" of the goals, the strategy and, partially, the payload of the ill-fated Russian Mars-96 that failed at launch in November 1996 (Martin et al. 2025, this collection; Bibring et al. 2025, this collection). During more than 20 years of operations, Mars Express has returned a rich harvest of scientific results, advancing our knowledge of Mars' interior, subsurface, geology, history and evolution, meteorology and climatology from the lower and middle atmosphere to the thermosphere and ionosphere.

Mars Express discoveries have played an essential role in furthering our understanding of the Red Planet's geological and climate evolution and in assessing its past habitability. Long-term series of atmospheric parameters (e.g., temperature, abundance of minor species, dust and clouds) delivered by Mars Express constitute a solid observational basis for developing advanced meteorological and climate models at various scales. Monitoring of the ionosphere and plasma environment over almost two solar cycles has revealed the complex behaviour of the upper atmosphere, including escape processes, as a function of external conditions (i.e., UV flux, solar wind forcing, distance to the Sun, crustal magnetic field) as well as the coupling between atmospheric layers. Regular encounters with Phobos have allowed

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characterizing the moon and its ephemeris in preparation for future *in situ* missions. All this has cemented Mars Express' role as a key mission in the field of comparative planetology.

The spacecraft and payload design, as well as the ground segment architecture, have proven very robust and flexible, allowing adjustment of the entire mission system in response to changing conditions, minimising resource needs and failures of equipment due to lifetime issues (Cardesín-Moinelo et al. 2024, this collection; Wilson et al. 2026, this collection). Continuous efforts by the engineering and science teams have kept the spacecraft and payload in very good shape, in some cases even enhancing its capabilities. Therefore, the 20-year-old spacecraft performs as if it were much younger than its "passport" age.

Mars Express has opened the way for further European exploration efforts such as the ExoMars programme. It is remarkable how this low cost mission has helped to establish a strong planetary science community in Europe, resulting in new missions to Mars and to other planetary bodies.

MEX is a valuable asset that continues to sustain fruitful international collaborations. It is also a relay orbiter supporting ESA and other agencies' missions, and an enabling element for Mars and Phobos observations in support of landing site characterization and selection. Mars Express has been extended until the end of 2026 with indicative plans to operate until the end of 2028.

This paper concludes the Topical Collection "Mars Express: Pioneering Two Decades of European Science and Exploration of Mars" prepared under the auspices of the International Space Science Institute (ISSI). It briefly describes various aspects of the mission leaving detailed presentation to dedicated articles. Section 2 briefly introduces Mars Express science goals, the spacecraft and payload. Section 3 highlights the major science achievements of Mars Express. Section 4 discusses important lessons that can be learned from more than 20 years mission life-time. Section 5 bridges with future science and exploration of the Red Planet after Mars Express, followed by a brief introduction of prospective studies and future mission concepts at ESA in Section 6.

2 Science Goals, Spacecraft and Payload

Mars Express was conceived and built by ESA as a successor of the ill-fated Russian Mars-96 mission and became the first flexible (F) mission of the new and inventive scenario of the ESA long term Scientific Programme Horizons-2000 with the launch in May-June 2003. With Mars Express Europe got a unique, low cost and low risk opportunity to join the scientific exploration of Mars (Martin et al. 2025, this collection; Bibring et al. 2025, this collection).

Science Objectives. Mars Express inherited most of its science objectives from the predecessor, Mars-96 mission. The Mars EXpress Science Management Plan (ESA 1997) formulated the orbiter's goals as "a high-resolution imaging and mineralogical mapping of the surface, radar sounding of the subsurface structure down to the permafrost, precise determination of the atmospheric circulation and composition, and study of the interaction of the atmosphere with the interplanetary medium". Specific objectives include (1) global geological mapping of the surface with down to 10 m/pixel resolution and building of the Digital Elevation Model (DEM) with about 50 m/px resolution; (2) global mineralogical mapping of the surface with down to few hundred metres per pixel resolution; (3) global characterization of the subsurface structure and properties at kilometre scale down to several km depth; (4) assessment of the interior structure; (5) global characterisation of the atmospheric structure, composition and chemistry, circulation and their variability; (6) characterization of the structure of the ionosphere, its variability and dependence on external conditions and understanding of Mars aeronomy; (7) characterization of the plasma environment and escape processes; (8) investigation of Phobos and Deimos. These specific objectives stem from the top level fundamental goals such as unveiling history and evolution of Mars and its climate, understanding the current climate and weather system and establishing couplings between different layers. Achievement of these objectives would result in significant progress in the field of comparative planetology of terrestrial planets and understanding of their habitability.

Spacecraft. Mars Express is a 3-axis stabilised spacecraft with dimensions 1.7x1.7x1.4 m with body-mounted instruments and two about 5 m long solar panels. The 1.65 m body-fixed High-Gain Antenna (HGA) operating in X and S bands has provided telemetry data rate of up to 228.5 kbps depending on the Mars-Earth distance. The total launch mass was 1223 kg, including the spacecraft platform, 113 kg of payload instruments, the 60 kg Beagle 2 lander, and 473 kg of bi-propellant (Martin et al. 2025, this collection).

Orbit. On June 2, 2003 the spacecraft was launched by Russian Soyuz-FG/Fregat launcher from Baikonour cosmodrome (Kazakhstan). Mars Express arrived at Mars in December 2003 after about 400 million kilometre cruise. The Beagle 2 lander was released on December 19 followed by Mars Express orbit insertion on December 25, 2003. After a series of orbit corrections the spacecraft reached its science orbit with 258 km x 11,560 km distance to the planet, 86.3° inclination, and 7.5 hours period. The orbit featured precession of the pericentre, i.e. the pericentre slowly drifts in meridional direction that allowed observations of all latitudes with high spatial resolution. Importantly, this orbit enabled atmospheric and ionospheric observations at all local times, regular close (∼50 km) Phobos flybys and crossings of the magnetospheric boundaries. Pericentre position alternating from day to night side enabled successive spectro-imaging and subsurface sounding campaigns each of which required quite different illumination conditions (Cardesín-Moinelo et al. 2024, this collection).

Payload. Mars Express inherited from the Mars-96 mission a powerful complement of seven instruments that has proven to be fully capable addressing not only original mission science objectives, but even the new ones that emerged during the 20 years of mission lifetime (Wilson et al. 2026, this collection). The geophysical payload suite comprises three instruments. The High Resolution Stereo Camera (HRSC) is aimed at geomorphological surface mapping. The Observatoire pour la Mineralogy, l'Eau, les Glaces et l'Activité (OMEGA), a visible and infrared hyperspectral imaging spectrometer, has been used for mineralogical analysis of the surface. The Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) characterised structure and physical properties of the subsurface. The atmospheric payload suite consisted of the Ultraviolet and Infrared Atmospheric Spectrometer (SPICAM) to study composition and structure of the atmosphere in nadir and solar occultation geometry, the Infrared Planetary Fourier Spectrometer (PFS), which sounded atmospheric temperature structure and composition, and Radio Science Investigation experiment (MaRS), which uses the communication radio link to probe the neutral atmosphere. Spectroscopic observations were supported by imaging capabilities of HRSC, OMEGA, and the Visual Monitoring Camera (VMC), a wide-angle context imager refurbished from a simple engineering camera that now is being used to study atmospheric structure and various meteorological phenomena and processes. The third payload suite focuses on investigations of the ionosphere, plasma environment and escape processes and includes MARSIS radar in the ionospheric mode, MaRS radio occultation experiment, and the Analyser of Space Plasmas and Energetic Ions (ASPERA-3) to characterise ions, neutrals and electrons around Mars. And, finally, Mars Express uses the UHF Radio System, MELACOM, originally designed to communicate with Beagle 2, to perform MEX-TGO Mutual Occultation Experiments to sound the ionospheric structure (Parrott et al. 2024).

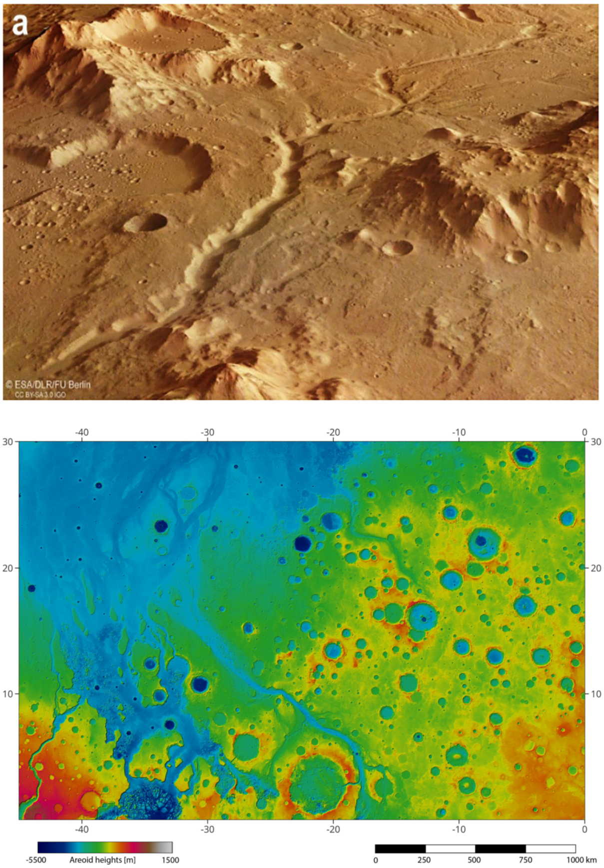


Fig. 1 Examples of HRSC high-level products: **(a)** oblique view of Lybia Montes showing an extensive valley network. HRSC color image is superimposed on the HRSC DEM. The valley width in the foreground measures about 1.5 km. Image bottom to horizon is about 50 km. (from Jaumann et al. 2024, this collection); **(b)** HRSC Level-5 multi-orbit DEM for Mars Quadrangle MC-11 (Gwinner et al. 2016; Tirsch and Gwinner 2024, private communication)

3 Mars Express Science Highlights

This section provides a brief summary of the major Mars Express science highlights discussed in more detail in specific papers of this Topical Collection.

Geology, interior and history. By 2023 the High-Resolution Stereo Camera (HRSC) onboard Mars Express had delivered almost complete (>87%) coverage of the surface by colour and stereo imaging at spatial resolution below 20 metres per pixel (Figure 1a) (Jaumann et al. 2024, this collection). The top-level science imaging product is the set of multi-orbit regional topography maps at 50 m/pixel resolution, provided so far for three 30° latitude × 45° longitude quadrangles (Gwinner et al. 2016). In addition, Putri et al. (2019) produced the Digital Elevation Model (DEM) of the Southern polar cap using a modified version of a NASA-VICAR-based pipeline developed by DLR (German Aerospace Centre) and JPL (Jet Propulsion Laboratory). The MEX DEM with 50 m ground sampling distance (Figure 1b) complements the "classical" global geodetic reference Mars Orbiter Laser Al-

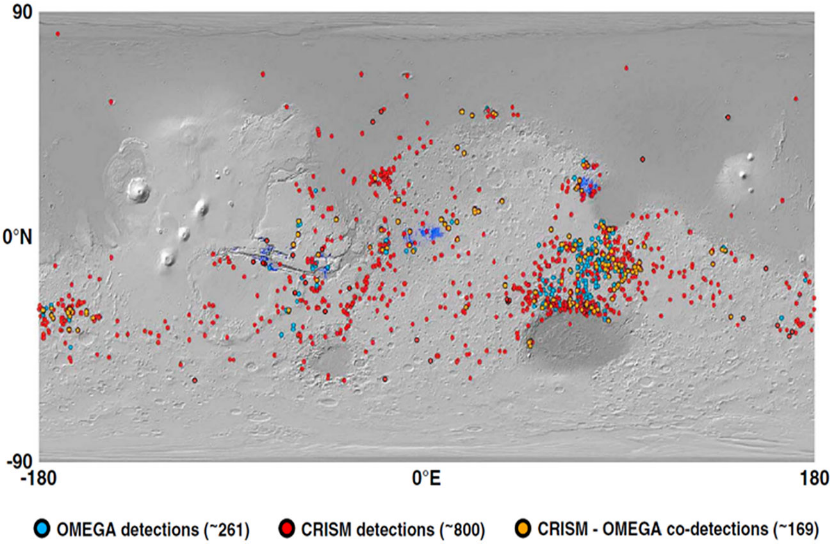


Fig. 2 Global distribution of hydrated minerals derived from the imaging spectroscopy by OMEGA/ MEX and CRISM/ MRO (Carter et al. 2025, this collection)

timeter (MOLA) topography with resolution of 463 m/pixel. The imaging that revealed the surface relief and age together with the global mapping of the surface composition and mineralogy at sub-kilometre resolution (Fig. 2) (Carter et al. 2025, this collection) allowed reconstructing the regional geology and history of the planet (Bibring et al. 2006, 2025, this collection, Jaumann et al. 2024) as well as establishing the relation between H_2O and CO_2 ices in the polar caps (Bibring et al. 2004). Mars Express observations have improved our understanding of formation scenarios for Nili Fossae, Arabia Terra, the Olympus Mons vicinity and other regions. MEX has provided quantitative characterization of glacial, fluvial, and sedimentary processes on Mars including their timing and periodicity (Jaumann et al. 2014, 2024, this collection).

Subsurface soundings obtained with the MARSIS penetrating radar have provided the third dimension for surface investigations, revealing buried geological structures down to several kilometres depth (Orosei et al. 2025, this collection). Of special interest has been the characterization of the Polar Layered Deposits (PLD) and the discovery of multiple subglacial water bodies underneath the Southern polar cap that triggered new modelling and theoretical efforts to explain the observations (Orosei et al. 2018; Orosei et al. 2025, this collection). Joint imaging by ESA's Mars Express, Trace Gas Orbiter (TGO) and NASA's Mars Reconnaissance Orbiter (MRO) at spatial resolutions ranging from 15 m/pixel to 25 cm/pixel has greatly enhanced our knowledge of seasonal processes on Mars continuously altering the topography (Thomas et al. 2024, this collection).

Atmospheric structure, composition and meteorology. Mars Express non-sun-synchronous, quasi-polar orbit has enabled complete local time and spatial coverage, with the SPICAM, PFS, OMEGA, and MaRS instruments to construct the longest (10 Martian years) record of atmospheric parameters, including temperature structure, abundance of minor species, distribution and variability of atmospheric dust and clouds (Fig. 3). The mission has explained thermal asymmetries between the western and eastern hemispheres in the southern high latitudes due to a planetary wave excited primarily by the middle-latitude

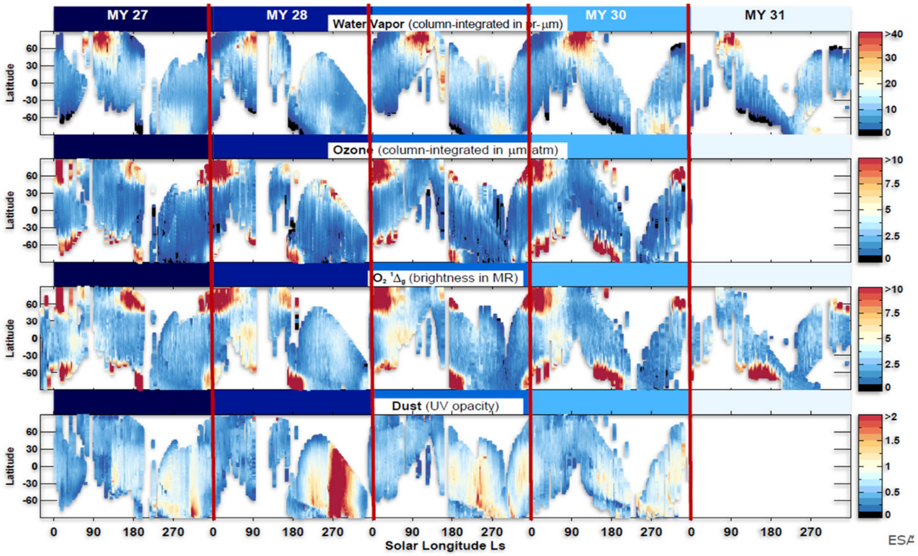


Fig. 3 Example of multi-annual survey of Mars atmospheric parameters performed by SPICAM in the nadir looking mode: water vapour column density (upper panel), ozone column density (second panel), molecular oxygen singlet delta daytime emission in the near infrared (third panel), and dust UV opacity (lower panel) (from Montmessin et al. 2017). Vertical red lines separate Martian years

surface topography, namely, the Hellas and Argyre basins. Mars Express has monitored peculiarities of the atmospheric temperature field, in particular, in the vicinity of Martian volcanoes, and changes related to dust storms (Giuranna et al. 2025, this collection). The mission has characterized the planetary boundary layer establishing correlation of its thickness with the surface elevation (Hinson et al. 2019).

Mars Express has revealed important details about the atmospheric annual water cycle: an increase in H_2O abundance at high altitudes during the perihelion season strongly enhances hydrogen escape (Fedorova et al. 2021; Montmessin et al. 2017, 2024, this collection). Long-term monitoring of ozone and water vapour has shown a distinct anti-correlation between their column abundances. This has provided insight into the hydrogen chemistry that stabilizes the atmospheric composition.

Mars Express discovered methane and its spatial variability (Formisano et al. 2004). Although methane on the planet was later detected by other experiments (for example the Sample Analysis at Mars (SAM) instrument on Curiosity), its presence is still elusive and its origin, chemistry and transport are enigmatic (Vandaele et al. 2024, this collection). Interestingly, the Trace Gas Orbiter (TGO), ESA's successor of Mars Express, that uses the solar occultation technique to study the distribution of minor species in the middle and upper atmosphere has not detected methane at the altitudes it can interrogate.

TGO observations have confirmed and provided additional detail to extend Mars Express findings, revealing new features and processes, like water vapour intrusion in the upper atmosphere during dust storms (Fedorova et al. 2020). The MEX, TGO and MRO orbiters have provided long-term monitoring of carbon monoxide, a key constituent of the photochemical carbon cycle largely responsible for maintaining atmospheric CO_2 stability. All measurements indicate significant CO depletion during the summer season, in anti-correlation with the annual CO_2 cycle. (Vandaele et al. 2024, this collection). The solar occultation technique

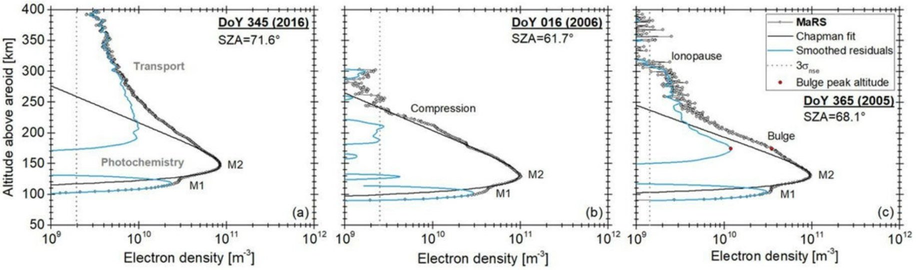


Fig. 4 Structure of the dayside ionosphere derived from MaRS radio-occultations. Gray circles show the electron density. Gray dashed line indicates the 3σ noise level. The black line is the result of a Chapman function fit on the ionospheric main peak region. The blue line indicates the smoothed residuals of the fit, i.e. deviation from the Chapman layer fit (from Peter et al. 2024, this collection)

combined with high spectral resolution have allowed MEX and TGO to monitor molecular oxygen and to sound atmospheric composition with unprecedented sensitivity. This led to the discovery of hydrogen chloride (HCl) and to the determination of upper limits for abundances of ethane (C_2H_6), ethylene (C_2H_4), phosphine (PH_3), and methane (CH_4) in the middle and upper atmosphere, as well as to constrain the ratio of hydrogen, oxygen and carbon isotopes (Vandaele et al. 2024, this collection).

Dust and cloud climate records have been derived from more than 10 years of Mars Express observations. They cover annual cycles, diurnal and spatial variability, evolution of dust storms and optical properties (Määttänen et al. 2024, this collection). Mars Express has investigated cloud morphology and dynamic phenomena at different spatial scales, as well as their seasonal and aerographic distribution and cycles by combining images captured by all cameras onboard MEX with those from other missions. The scientific potential of the imaging suite was greatly enhanced by the conversion of the Visual Monitoring Camera (VMC), a simple, low-cost instrument initially developed for engineering purposes, into a science tool that has been included in regular payload operations. In particular, the imagers have monitored planetary scale features (aphelion cloud belt, global dust storms, circumpolar dynamics, cyclone systems), mesoscale (orographic clouds, ground fogs, dust layers) and small-scale phenomena (waves, dust devils). The most remarkable discovery was the transient water ice cloud at Arsia Mons - the longest (∼2000 km) orographic cloud observed in the Solar System so far (Sánchez-Lavega et al. 2024, this collection).

Ionosphere and aeronomy. Non-sun-synchronous, highly elliptical orbit, and long mission duration covering consecutive solar minima 23/24 and 24/25 have enabled a complete characterization of the topology and variability of Mars' ionospheric and magnetospheric boundaries (Fig. 4) (Hall et al. 2019; Peter et al. 2024, this collection). Long-term series of observations by the MARSIS ionospheric radar, MaRS radio-occultation experiment, and ASPERA-3 plasma package have revealed variability in the ionospheric structure and total electron content with solar zenith angle and Sun-Mars distance, the role of the crustal magnetic field and atmospheric cycles as well as determined the pressure balance at the ionopause (Bergeot et al. 2019; Sánchez-Cano et al. 2018, 2021; Peter et al. 2024, this collection). Similar monitoring of the Venus ionosphere supported by modelling efforts has enabled comparative analysis of the ionospheres of both non-magnetic planets (Peter et al. 2014). Mars Express has also investigated coupling processes between atmospheric layers. In particular, the mission has revealed the role of dust storms in enhancing the variability of the upper atmosphere. For instance, the global dust storm in MY28 raised the altitude of the main ionospheric peak by 10–15 km (Peter et al. 2023).

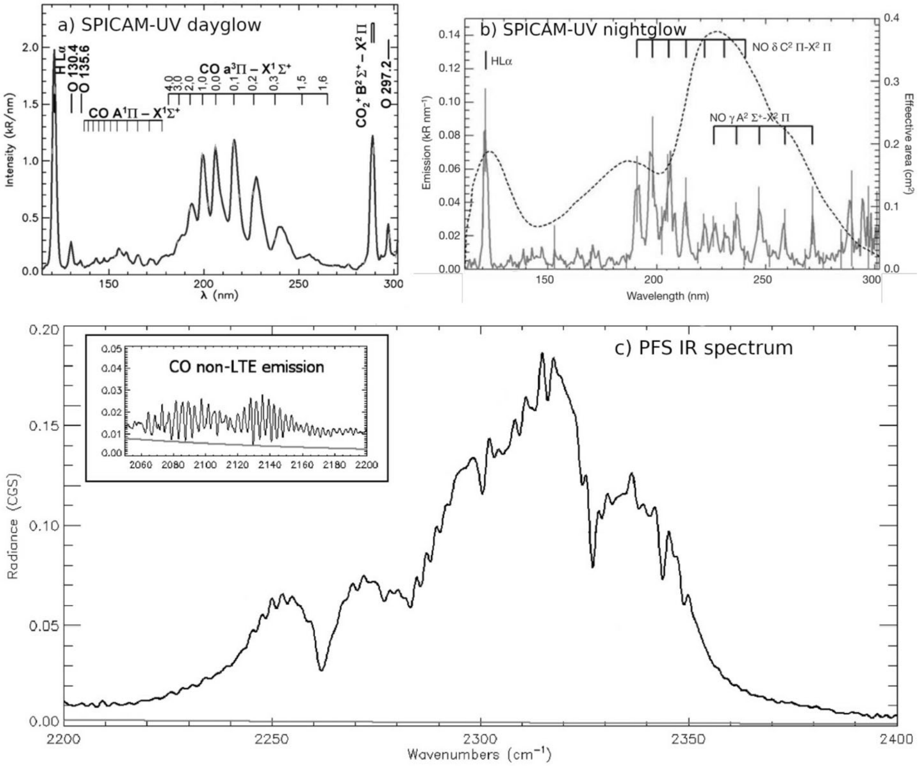


Fig. 5 Average UV spectra measured by SPICAM on the dayside (panel a)) and the nightside (panel b)). Panel c) shows average IR spectrum of CO_2 and CO (inset) emissions measured by PFS (from Gonzáles-Galindo et al. 2024, this collection)

The start of the Mars Express science mission in 2004 marked the beginning of a golden era for the study of the Martian airglow and aurora. The mission discovered aurorae and nightglow emissions (Fig. 5) (Bertaux et al. 2005a, 2005b; Leblanc et al. 2006). The powerful spectrometer suite onboard Mars Express has taken advantage of different observation geometries that facilitated a breakthrough in our understanding of Mars' aeronomy (González-Galindo et al. 2024, this collection). The nadir and limb observations of CO_2 non-LTE (Local Thermodynamic Equilibrium) emission at 4.3 µm allowed validating non-LTE models. By probing the Lyman-α emission from the upper atmosphere the mission established the link between water vapour in the lower and middle atmosphere and atomic hydrogen in the thermosphere (Montmessin et al. 2024, this collection). Discovery and monitoring of H and NO nightglow emissions on Mars have enabled the characterization of thermosphere dynamics, the coupling between atmospheric layers and hydrogen escape. Mars Express detected discrete auroral emissions and established their connection to the regions of strong crustal magnetic field. The pioneering MEX observations were later expanded and complemented by TGO, MAVEN and Hope.

Plasma environment and escape. Mars Express has provided the longest time series of solar wind and atmospheric escape monitoring during solar cycles #24 and #25 for the first time covering a complete solar cycle. The mission, and, in particular, the ASPERA-3 instrument, made a pioneering and fundamental contribution for understanding the interaction of

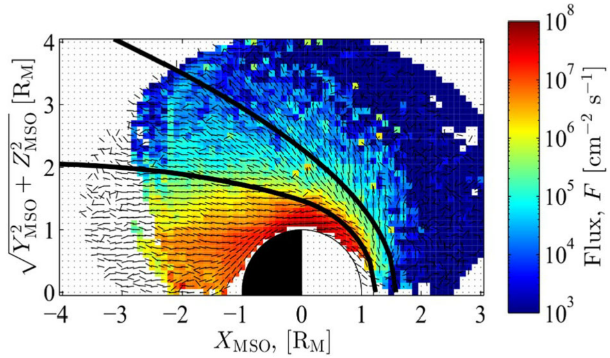


Fig. 6 Time-averaged O^+ outflow from Mars in cylindrical coordinates. The upper black solid line shows the bow shock while the lower one is induced magnetosphere boundary (from Barabash et al. 2025, this collection)

the solar wind with a non-magnetized planet, and to characterize the ion escape at Mars and its role in atmospheric evolution (Fig. 6). Advanced plasma instrumentation (ASPERA-3 and MARSIS) and a relatively high data rate have provided a detailed *in-situ* view of the ion distribution, which can be tracked from the top-side ionosphere to the deep induced magnetotail thanks to the spacecraft's elliptical orbit. The long operational life of Mars Express has allowed the mission to obtain measurements during rare extreme events, such as coronal mass ejections and solar energetic particles (SEP) events —which can represent conditions in the early solar system—, or the encounter with the comet Siding Spring (Barabash et al. 2025, this collection).

Data analysis indicates that ion escape from Mars is limited by the supply of ions from the ionization source region and, thus, depends strongly on EUV flux (the mechanism responsible for the ionisation of neutrals). Ramstad et al. (2019) concluded that ion escape plays a minor role in the evolution of the Martian atmosphere and cannot account for an atmospheric loss mechanism consistent with the geological record. Other, more efficient escape channels have been revealed by NASA's MAVEN mission (Jakosky et al. 2018 and references therein).

One of the fundamental MEX results with implications extending beyond Mars has been a re-assessment of the role that intrinsic magnetic field have in the overall evolution of planetary atmospheres. Before Mars Express it was thought that magnetospheres created by an intrinsic magnetic field form a “bubble” that protects the ionosphere from solar wind erosion. However, long-term monitoring of Mars, Venus and Earth suggest that, on the contrary, the ion escape rate increases on a magnetized planet due to a larger cross-section and thus greater energy injected in the magnetosphere by the solar wind (Ramstad and Barabash 2021). On Earth, this mechanism has been studied for many years. In a diverging magnetic field configuration, as that on polar cusps, transverse excitement of ions by electrostatic waves in the auroral region results in the formation of ion conics allowing ions to escape along field lines (see for example, Vago et al. 1992, 2017).

Mars Express has provided valuable support to other missions, in particular NASA's MAVEN, by monitoring the upstream solar wind. A new active sounding method of the plasma environment - by measuring the ions accelerated by MARSIS radar pulses - was developed and implemented, allowing for *in-situ* mapping of the ion density (Barabash et al. 2025, this collection).

Martian moons. The highly eccentric orbit of Mars Express has enabled more than 200 flybys of Phobos at a distance ≤1000 km, with a closest approach of 50 km (Witasse et al. 2014). The moon's surface has been mapped (almost completely) by HRSC at a spatial resolution of 5 m/px. Spectroscopic observations by OMEGA and SPICAM have indicated the presence of pyroxenes, olivine, and phyllosilicates, as well as of polycyclic aromatic hydrocarbons (PAH) and ilmenite, a titanium-iron oxide mineral. The mission's multi-object imaging of Phobos and Deimos and spacecraft tracking by MaRS radio science experiment significantly improved the moons ephemerides, as well as the global shape model that was essential for refining the moons' volumetric data and density (Pätzold et al. 2024, this collection). These data and subsurface sounding by MARSIS led Andert et al. (2010) to conclude that Phobos is a porous body, possibly accreted from debris in Mars orbit, and is not a captured asteroid. Recently, a new ASPERA operation mode allowed the particle detector to measure solar wind ions scattered by Phobos. With the abovementioned results Mars Express significantly contributed to the preparation of JAXA's Martian Moons eXploration (MMX) mission to Phobos.

4 Lessons Learned from Mars Express

Mars Express is the first F (Flexible) mission of ESA. After the ill-fated Russian Mars-96, the agency had limited funding and schedule resources for implementing a new mission. In fact, the project development scheme chosen for the mission was unusual in many ways. It granted much more responsibility to industry and followed a "fast track" implementation (Martin et al. 2025, this collection). This notwithstanding, MEX possesses unique features and advantages that have made possible successful operations and high science return for more than two decades. Important lessons learned from Mars Express are presented below.

4.1 Mission Architecture and Design

Mars Express was set up as a multi-disciplinary survey mission addressing almost all Mars science disciplines, such as planetary evolution, geology and history of water, current and past climate, meteorology and chemistry of the atmosphere, role of dust and coupling between atmospheric layers, aeronomy and interaction of an unmagnetized planet with the plasma environment. The longevity of the mission has enabled constructing the longest record of Mars climatology, ionospheric and plasma parameters so far. This has proven essential for furthering our understanding of meteorology, climate and planetary evolution. Mars Express is the only spacecraft to have performed almost uninterrupted plasma environment monitoring for more than one solar cycle. The long mission duration also increases the probability of observing unplanned transient events, like extreme solar wind or the 2014 encounter with the comet Siding Spring. The mission has provided global context and reference data for other, more focused missions such as NASA's MAVEN in the field of aeronomy and evolution, or the ESA-Roscosmos Trace Gas Orbiter for atmospheric composition and chemistry.

Mars Express benefited from the flexible spacecraft platform and payload development of the Rosetta design. The three missions, Rosetta, Mars Express and Venus Express, form the so-called "Rosetta Family", with strong synergy in spacecraft and payload procurement, as well as in operations and data exploitation.

Lesson #1. Robust and flexible spacecraft, payload, and ground segment capable of adapting to varying conditions and mission resources has proven very efficient for fulfilling the original science goals and defining new ones.

Lesson #2. Mission longevity is essential, especially for investigation of the dynamic systems, like atmosphere, ionosphere and circumplanetary plasma environment.

Lesson #3. The reuse of mission concepts, design, and elements can offer significant reductions in development costs and time, and eventually increase the overall science return.

4.2 Orbit

The Mars Express orbit is perfectly suited to the mission's science goals. This quasi-polar, non-Sun-synchronous, eccentric (250 km × 11,500 km) orbit has allowed the spacecraft to observe the planet at all latitudes and local times. A natural latitudinal pericentre drift has enabled surface mapping of the entire planet at close distance. In the apoapsis section the orbit crosses ionospheric and magnetospheric boundaries, performing "tomography" of the plasma environment at all local times, within a large range of distances and viewing geometries. The orbit configuration also enables regular Phobos flybys with 50-km approaches.

Lesson #4. Selection of a proper orbit is essential for achieving a broad coverage of the mission parameter space —i.e. planetocentric latitudes and longitudes, local solar time, and distance to the planet— that is a key prerequisite for fulfilling mission objectives in all science fields.

4.3 Payload

The Mars Express payload consists of seven instruments, all inherited from Mars-96, addressing a broad palette of scientific disciplines (Wilson et al. 2026, this collection). We emphasise here the synergistic nature of the payload suite, which enables a multifaceted view of phenomena and processes on the planet. Even nowadays, at a time when more sophisticated and powerful instruments operate at Mars, the MEX payload occupies an important and unique science niche. The instruments have demonstrated the ability to adjust to new science inputs and tasks, including changes in operational modes, adaptation of observation strategies, and even the conversion of engineering instruments into scientific ones.

Lesson #5. A synergistic payload suite working in concert to address the mission's scientific objectives is essential for maximizing the science return.

4.4 Mission and Science Operations

Mars Express established the baseline for the development of ground segments for most ESA planetary missions (e.g. Venus Express, Trace Gas Orbiter). Their Science Ground Segment definition, procedures, tools and even personnel have been largely inherited from Mars Express. In these two decades, the MEX operation teams have gained excellent knowledge and high confidence in the performance of the spacecraft platform and its payload (Cardesín-Moinelo et al. 2024, this collection). This has resulted in a great level of flexibility in science and mission operations. In particular, the spacecraft pointing capability has been very much expanded over the years. The remote sensing suite is now capable of observing targets in almost any direction and at any time within the orbit, allowing specific distances and illumination conditions that were not possible in the past (Phobos, limbs, and target tracking).

Lesson #6. The mission and science operations system should be robust and flexible to respond to changing conditions, resources, and modification of science objectives and priorities. Of high importance is tight collaboration and understanding between mission science and engineering teams.

4.5 Data Archiving and Science Exploitation

Standard for ESA planetary missions, Mars Express experiments are required to regularly archive their primary calibrated data in the Planetary Science Archive (PSA) following a proprietary period of 6 months. The experiment teams have used this time for quick-look analysis, validation, calibration, and preliminary science assessment (Cardesín-Moinelo et al.

2024, this collection). In general, the Mars Express teams manage to cope with the large amount of acquired data, but archiving has been often perceived as a "bottleneck" in data dissemination to the science community.

Lesson #7. *Proper and timely archiving of the primary calibrated data and corresponding documentation by PI teams and ESA is an essential and urgent need of the science community and key to disseminate the mission's results. Improvement of the data archiving urges tighter collaboration between ESA, Lead Funding Agencies and PI teams as well as stronger support to all parties involved in this activity.*

Lesson #8. *Increased support to instrument teams that can facilitate shortening the prior-access period, as well as measures for streamlining the PSA data validation cycle, would allow releasing data after a preliminary check, permitting a faster involvement of the broad science community in the data analysis.*

Calibration of the primary data (images, spectra, frequency residuals, etc), whose archiving is ESA's responsibility, is only the first step in data analysis. The data often require further, and sometimes rather complex, processing before they can become usable by scientists. Therefore, archiving of *high-level data products* (e.g. mineralogical maps, temperature profiles, distribution of trace gases and clouds, etc) in the PSA and/or ESA's Guest Storage Facility (GSF), in addition to the primary calibrated data, would be a much appreciated service to the science community, significantly increasing the science return of planetary missions. The Mars Express team has prepared a dozen high-level data products for archiving. We note, however, that the archiving of high-level data products is still done on a best-effort basis and is not yet fully incorporated into the ESA system.

Lesson #9. *Full inclusion of high-level data archiving in the ESA PSA process would significantly improve dissemination of mission results within the science community and enhance overall ESA science return.*

Mars Express has provided an excellent example of how spacecraft *housekeeping data* can be used for science purposes in the field of heliophysics. Sánchez-Cano et al. (2023) utilized the readings of the Error Detection and Correction (EDAC) memory counters for a feasibility study of solar energetic particle event detections using ESA's fleet of solar system missions. This work has demonstrated that EDAC data can provide a network of solar particle detections at various locations in the solar system where no scientific observations of this kind are available. Archiving of subsets of these data is highly desirable for the future.

Two decades of Mars Express operations have demonstrated importance of timely data analysis. Broadening of the science community involvement in the data exploitation *beyond* the instrument teams would enhance the science return and support science operations planning. At present, ESA is not responsible for *science* data analysis and this work is done by science team members at institutes and universities. Sometimes, this can result in the data analysis effort being too dispersed and, in some instances, not adequate to deal with the quantity and quality of the data delivered by planetary missions.

Lesson #10. *A dedicated programme of science data exploitation under ESA or European Union aegis and guidance would consolidate the efforts of the science community and enhance the science return of ESA missions.*

4.6 Team

Over the past two and a half decades, several generations of scientists and engineers have worked on Mars Express (Martin et al. 2025, this collection). The long duration of the mission has proven the importance of achieving continuity and sustainability in mission and payload teams. This includes establishing mechanisms of knowledge preservation and transfer, as well as attracting, educating, and training young scientists and engineers. Renewal of the science teams would strongly benefit from the involvement of new institutions, universities and ESA Member States in missions already in operation. Such mechanisms as Interdisciplinary Scientists (IDS) and Guest/ Participating Scientists should be used more extensively and flexibly. Of vital importance is sufficient and continuous funding of operations teams at ESA and payload teams in the Member States.

Lesson #11. To ensure continuity and sustainability of long-lasting planetary missions, mechanisms of knowledge transfer and renewal of operations and science teams should be established.

Lesson #12. A targeted ESA support to the PI teams implemented on Mars Express has proven to be an effective tool for solving urgent issues in the area of operations, data archiving and analysis.

4.7 Complementarity and Collaborations with Other Mars Missions

Mars Express is a major element of the international Mars exploration effort, supporting other missions for science, critical operations, and data relay (Cardesín-Moinelo et al. 2024, this collection). The main synergies and complementarities with other, contemporaneous Mars missions are outlined in more detail below (see also Martin et al. 2025, this collection).

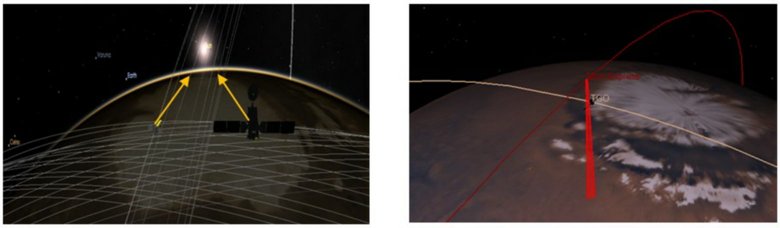
Trace Gas Orbiter (*ESA*). The scientific objectives of ESA's ExoMars Programme were defined largely on the basis of Mars Express findings, particularly in planetary evolution. The TGO payload design shares a strong heritage with MEX and VEX (Venus Express). In particular the ACS-TIRVIM/TGO stems from the PFS/MEX instrument (Korablev et al. 2018) and the NOMAD design is a direct evolution of the SPICAV-SOIR/VEX spectrometer (Vandaele et al. 2018).

Collaborations across MEX and TGO science teams; for example, between the HRSC and CaSSIS cameras, as well as with the SPICAM, PFS, OMEGA and NOMAD and ACS spectrometers; are well established and have produced great results.

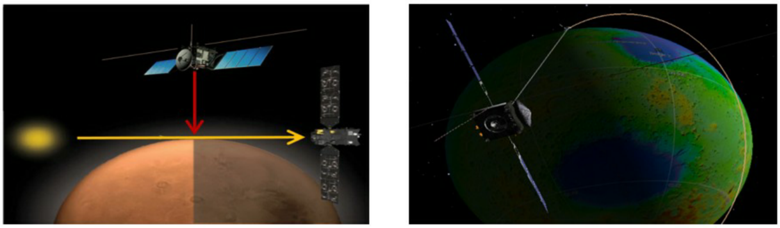
The synergies between MEX and TGO can be summarised as follows:

(1) Mars Express monitoring of the lower atmosphere ($<$20 km) is complemented by TGO observations of the middle and upper atmosphere, enabling to study coupling mechanisms between the layers.
(2) The development of mutual MEX-TGO UHF radio occultation experiments allows almost unconstrained (i.e. covering all latitudes, longitudes and local times throughout the mission) sounding of the ionosphere and —to a certain extent— of the neutral atmosphere as well.
(3) MEX context imaging and digital elevation models (DEMs) provide geodetic reference datasets for co-registering and analysis of data from instruments on other missions, *e.g.*, CTX, HiRISE, CaSSIS, SHARAD.
(4) Mars Express is able to investigate the polar regions ($>$75° latitude), which are not accessible by TGO.
(5) Coordinated MEX-TGO observations permit discriminating between spatial and temporal effects.
(6) It is possible to conduct MEX-TGO cross-calibration of instruments and of retrieval techniques.
(7) MEX-TGO can ensure continuous monitoring of atmospheric parameters.

The scientific objectives of MEX and TGO are highly complementary, especially for atmospheric studies. Therefore, the science teams have made efforts to perform joint investigations. Hundreds of coordinated atmospheric observations have been conducted (Fig. 7) The



MEX/TGO solar occultation MEX/TGO nadir crossing



MEX over TGO sun occultation MEX-TGO radio occultation

Fig. 7 MEX-TGO coordinated observations (Cardesín-Moinelo et al. 2021)

spectrometers SPICAM/MEX and ACS-NOMAD/TGO carried out quasi-simultaneous and almost collocated solar occultation experiments, comparing vertical atmospheric profiles separated by no more than 15 minutes and a distance of less than 1000 km. Both satellites investigated the same location in nadir geometry, with crossing points within 350 km —or less than 5 degrees as seen from Mars. Additionally, Mars Express usually observes nadir in the region of TGO solar occultations, obtaining wider contextual imaging and temperature retrievals to complement vertical atmospheric profiles. Lastly, spacecraft-to-spacecraft UHF radio occultations were validated in 2021 and are now being conducted routinely providing ionospheric sounding in great detail. Implementation of the joint MEX-TGO observation programme became possible thanks to strong coordination of operations of both spacecraft (Cardesín-Moinelo et al. 2021).

The coordinated observations by the two missions provide valuable information for comparing atmospheric retrievals, the study of temperature, composition and meteorology, as well as for instruments cross-calibration. Cardesín-Moinelo et al. (2021) summarized the main atmospheric parameters that can be observed simultaneously by the different instruments onboard Mars Express and TGO, including atmospheric temperatures, dust, CO_2 ice, water ice, water vapour, CO and methane (see Table 1 therein).

Mars Atmosphere and Volatile EvolutioN (*MAVEN*) (*NASA*). Mars Express has established a fruitful collaboration with NASA's MAVEN mission for instrument cross calibration, solar wind monitoring, conducting two-point plasma measurements, and for coordinated observations and joint data analysis. MEX soundings of the lower and middle atmosphere and MAVEN detailed investigations of the upper atmosphere have enabled studying complex couplings between atmospheric layers. In particular, the transfer to the upper atmosphere of hydrogen atoms from water vapor in the lower and middle atmosphere, a central question for water escape, is addressed in a complementary manner. Following the lowering of the MAVEN orbit in 2019, Mars Express provides a vital support by monitoring upstream solar wind parameters.

Martian Moons eXploration (*JAXA*). Mars Express supports JAXA's *Martian Moons eXploration* (*MMX*) project with regular observations of Phobos and Deimos for creation of a global shape model, the improvement of the moon's ephemerides, as well as sharing data and expertise. The evolving Mars Express database is crucial to MMX science objectives, mission planning and for selecting sample return sites on Phobos. Upon MMX arrival at Mars, both missions plan to conduct coordinated observations of Mars and its moons.

Landing sites selection. Mars Express observations have contributed to the characterisation of potential landing sites. Hyperspectral IR data from the OMEGA instrument and multispectral data from the High-Resolution Stereo Camera (HRSC) inform global, regional and local studies in support of planning for landed missions.

The utility of HRSC image data and stereo-derived terrain models fs cannot be overstated. A typical first step in setting up a project in a Geographic Information System (GIS) is to establish a base map layer onto which other data may be co-registered. HRSC images serve well as base layers for landing site studies due to their optimal spatial resolution (12.5 m/pixel for the broadband channel at nadir), coverage, radiometric consistency and spatial contiguity, for typical study site sizes of 1000-10s km. HRSC data usefulness has been further enhanced with the production of regional mosaics organized into a global scheme (Gwinner et al. 2016).

A wealth of results from OMEGA (Carter et al. 2013; Gendrin et al. 2005), corroborated and built-upon by results from the MRO CRISM instrument (Murchie et al. 2007), have profoundly advanced our understanding of early Mars mineralogy and evolution. Hyperspectral data provide overviews of surface mineralogy from global to site-specific scales, via the parameterization of key spectral features as spectral indicators (Pelkey et al. 2007). Such data enable interpretation of large-scale processes that may be tied to regional and global chronology of Mars' surface and climate. Clearly, such valuable insight is key for targeting and evaluating the scientific potential of landing site candidates.

Investigations of the Mars atmosphere also support the study of landing sites via observation of atmospheric phenomena and the assessment of atmospheric conditions relevant for entry, descent and landing (EDL), as well as for the operation of landed spacecraft. Mars Express instruments most capable of plasma and atmospheric observations and measurements (ASPERA, PFS, SPICAM, MaRS, and VMC) have provided valuable results relevant for planning of future landed missions. Most pertinently, the results inform the development of Global Circulation Models (GCMs) such as the Mars Climate Database (MCD)/Planetary Climate Model (PCM) (Millour et al. 2022).

Orbital radar signatures, though challenging to resolve at high spatial resolution from orbit, can provide meaningful constraints on surface and subsurface properties important for landed missions. Large-scale subsurface features, such as those caused by basal reflectors beneath polar layered terrains (Orosei et al. 2018) may drive the development of hypotheses testable by future missions. Indeed, the upper and deep subsurface of Mars are a primary target for addressing major questions in astrobiology, climatology, geology and other fields.

Other missions. The collaboration with NASA's Mars Reconnaissance Orbiter (MRO) and Mars Odyssey has been beneficial for advancing geologic investigations, surface mineral mapping and subsurface sounding. Of high value is the regular monitoring of the atmospheric conditions and minor species by PFS over Gale crater where NASA's Curiosity rover conducts *in-situ* measurements.

The collaboration with the Chinese Tianwen-1 mission has included geology and surface science, subsurface radar sounding, ionospheric and plasma investigations. HRSC images and DEMs, OMEGA mineralogy maps as well as the teams' expertise were used to characterise the Zhurong, Mars-2020, ExoMars Rover and Insight landing sites. The atmospheric science has benefitted from new Mars Express collaboration with Tianwen-1 and Hope (United Arab Emirates) orbiter missions. This triad can also provide multi-point plasma measurements for the first time at another planet.

Mars Express has also contributed to multi-spacecraft investigations of interplanetary processes, like coronal mass ejections (Witasse et al. 2017; Sánchez-Cano et al. 2023). The spacecraft performs coordinated observations with ground-based telescopes and the James Webb Space Telescope (JWST). Of particular importance are joint campaigns for the characterisation of minor species, CO_2 isotopes and dust. The ASPERA-3 experiment supports XMM-Newton's X-ray observations of Mars by solar wind measurements. VMC collaborates with the Mars Orbiter Mission of India.

Lesson #13. Collaboration between missions currently operating at Mars is essential. It has two aspects. Firstly, it enhances science return from the missions involved. Secondly, collaboration in operations (e.g. data relay support) increases safety during crucial phases (like EDL) and enhances mission performance.

4.8 Mars Express and the European Planetary Science

As the first ESA planetary mission, Mars Express played a pioneering role in establishing and building European planetary community and expertise. More than 150 PhD theses based on the mission data have been researched and successfully defended all over the world. The next generation of young scientists has evolved and matured, joining science teams for subsequent planetary missions, as well as leading the development of numerical models. Mars Express interdisciplinary science serves as a cohesive common ground unifying the Mars science community in Europe. The ESA-Roscosmos TGO mission, a direct successor of Mars Express, is the most important example of this legacy. Mars Express and its follow up, Venus Express, have made giant strides in the advancement of our knowledge in the field of comparative planetology.

Lesson #14. Planetary science strongly benefits from using comparative planetology as a consolidating principle. The science community grown and built around and thanks to one planetary mission can successfully apply the knowledge and expertise obtained to advance in the exploration of another planet due to common physics and similarity in experimental and modelling approaches.

5 Mars Science After Mars Express

5.1 Major Open Questions and Perspectives

Surface and interiors. In the last two decades, the main strategy for Mars surface imaging has been to improve spatial resolution. The net result of these efforts is expected to be a semi-global DEM with spatial and vertical resolution of about 50 m/pixel and 10 m, respectively, based on Mars Express stereo and colour imaging with about 12 m/pixel resolution (Gwinner et al. 2016). The DEM is amended by individual images at higher resolution of up to 0.3 m/pixel provided by other missions —that, however, cover a much smaller portion of the Mars surface. Future high-resolution imaging should be focused on selected areas depending on particular science goals and be co-registered with the global DEM.

The future Mars exploration strategy relies on *in situ* studies by rovers and landers. The NASA rovers operating on the Martian surface have proven their efficiency as "field geologists". Continuation of these studies at habitability-interesting locations is the most favourable approach. The missions will be equipped with drilling capabilities in order to access shallow subsurface (few metres deep) where any evidence of possible past biological activity on Mars would be best preserved (see Sect. 4.2).

Characterizing the fate and state of water ice deposits would provide valuable scientific and resource targets, while simultaneously contributing to establishing Mars' environmental history. Indigenous water is considered a crucial resource for future human-landed missions on Mars. A world-leading drilling capability has been developed by Europe through the ExoMars programme which will demonstrate metre-level drilling on Mars for the first time. This capability is now being transferred to lunar applications for the PROSPECT drill development that will access potentially icy soils on the Moon. ESA is now undertaking technology development activities to extend its drilling capabilities to greater depths that would be relevant for future Mars missions.

NASA's InSight lander detected thousands of Mars-quakes indicating ongoing internal activity. Following this discovery, a network of seismometers deployed on the Mars surface would improve our knowledge of interior structure and processes. Important advances for the understanding of geology and history of the Red Planet are expected from analysis of returned samples from Mars (see Sect. 5.4).

Atmosphere and climate. The previous and currently operational missions at Mars, including Mars Express, have provided an initial understanding of the planet's global atmospheric structure, composition, cloud morphology and circulation. The longtime series of observations have proven especially efficient at revealing dynamical processes and interactions that drive atmospheric and climate variabilities. Future studies should target atmospheric changes, for which coordinated long-term monitoring of the Martian atmospheric system would be essential.

Mars Express has demonstrated the high scientific potential of continuous global multispectral imaging of atmospheric dynamics and dust storms investigations (Sánchez-Lavega et al. 2024, this collection). The atmospheric features should be tracked from a high-altitude orbit with sufficient spatial and temporal resolution, thus enabling analysis of their morphology, motions and evolution. A non-sun-synchronous orbit would be beneficial for the analysis of local time changes. A similar strategy will be used for detection and investigation of transient atmospheric phenomena. We can conclude that high-altitude, simultaneous, global and continuous coverage of the planet, as proposed by several future mission proposals and studies (Montabone et al. 2021a), would be key for better understanding of Mars meteorology and dynamics.

For global weather monitoring from orbit, many studies focus on networks of small-to-medium size satellites, potentially in Mars equatorial, areostationary ($\sim$17,000 km altitude) orbits which offer advantages for the continuous global observation of Mars, as well as for communications (prolonged access, although at much lower data rates when the distance to the surface is large) and navigation applications in support of lower orbiters, surface landers and rovers, paving the way for future human exploration (Montabone et al. 2021a).

A minimal satellite constellation would consist of three small satellites in circular quasi-areostationary or areosynchronous orbit, spaced 120 degrees apart to offer global continuous longitudinal coverage, with a small remote sensing payload suite of multi-band visible-to-thermal infrared cameras and an IR spectrometer to retrieve atmospheric profiles of physical properties (pressure, temperature), composition (water vapor, trace gases, aerosols) and dynamics (winds). A modest space weather package to monitor magnetic field and solar wind interactions would consist of at least a magnetometer, solar wind ion/electron detectors and a radiation monitor (Montabone et al. 2021b).

A surface lander weather network would provide regional scale meteorology, with quasi-continuous day/night observations, measuring local atmospheric properties and retrieving vertical profiles of pressure, temperature, humidity, solar radiance, winds, dust properties, etc. The combination of a surface lander network and an orbital satellite network would allow simultaneous wind and dust storm observations at global and regional scales, in particular monitoring the origin and evolution of dust storms, which is of great importance for Mars surface missions and future human exploration.

Although the vertical structure of the Martian atmosphere as well as its large-scale variations are relatively well understood, resolution and coverage (spatial, vertical and temporal) are not sufficient for the study of small-scale features like, for instance, those typical for the boundary layer. Also, the evolution of the temperature structure during dust storms, when atmospheric opacity is high, remains virtually unexplored. The dual-spacecraft radio occultations, that were tested by NASA's MRO and Mars Odyssey spacecraft and that are currently being implemented by Mars Express and TGO orbiters, will enhance spatial and temporal coverage of the temperature sounding (Parrott et al. 2024; Nava et al. 2025).

Both ESA Explore 2040 (ESA 2025) and and the Planetary Science and Astrobiology Decadal Survey (NAS 2023) have identified weather monitoring as a key element of future Mars exploration programmes resulting in several mission concepts currently under study (MEPAG White Paper 2020; Parfitt et al. 2021). Meteorological investigations would strongly benefit from a network of permanent meteorology stations on the surface of Mars. Such detailed atmospheric observations would provide support for future human missions to Mars.

The very powerful spectrometer suite onboard TGO delivers highly sensitive and precise data on composition of the upper and middle atmosphere. However, even in clear condition the solar occultation measurements seldom penetrate below 10 km due to dust. Sensitive composition measurements in the lower atmosphere would unveil details of the chemistry of this region, chemical interactions with the surface and atmospheric dust. In particular, the "methane enigma" could be resolved through sufficiently sensitive nadir soundings (Korablev et al. 2019).

Ionosphere and aeronomy. At least until 2026, Mars Express will continue characterization of Martian airglow and aurorae in close collaboration with the TGO, MAVEN, and Hope missions. Single-spacecraft observations would not be able to provide the whole picture of the Martian plasma dynamics and real-time response to the variability of internal and external drivers. Therefore, a coordinated multi-spacecraft fleet enabling high spatial and temporal resolution plasma measurements would be a logical step forward. The M-MATISSE proposal to ESA aims at characterizing the couplings between the magnetosphere, the thermosphere, and the ionosphere by simultaneously operating two spacecraft. It is currently in competition for the next ESA M7 opportunity (Sánchez-Cano 2023). If adopted, M-MATISSE would be able to map auroral emissions on the nightside while simultaneously investigating the drivers of the auroral emission. The experience gained by the European teams on airglow and aurorae on Mars can be extremely useful in view of future missions to Venus (González-Galindo et al. 2024, this collection).

NASA‘s EscaPADE mission that, at the time of writing is being prepared for launch, will unravel the cause-and-effect that solar wind control has on ion and sputtering escape by measuring the temporal variability of the upper ionosphere with two spacecraft passing through the same region a few minutes apart (Lillis et al. 2023). NASA's MOSAIC high-level mission concept study (2019-2020) suggests ten coordinated spaceborne observation platforms to investigate the drivers of matter and energy flow between and within Mars' diverse climate domains (Lillis et al. 2021). These missions are the first steps on a road to achieving a deeper understanding of the variability of the Martian ionosphere and climate.

Plasma environment and planet evolution. Mars Express and other missions' observations have revealed key aspects of Mars evolution (Bibring et al. 2006; Bibring et al. 2025).

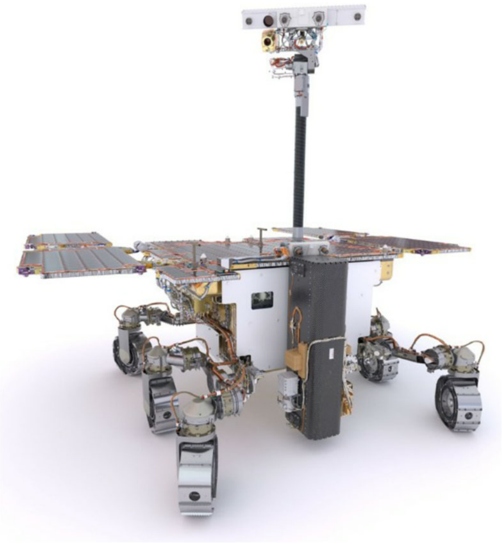


Fig. 8 Artist depiction of the Rosalind Franklin rover with the drill box in drilling position

The results regarding the volatile inventory, water in the first instance, on ancient Mars are inconsistent with the existence of a dense, warm and wet atmosphere in the Noachian epoch (4.1-3.7 By ago) (Wordsworth et al. 2021; Jakosky et al. 2018). This calls for further investigation of the plasma environment and escape processes, especially using coordinated multi-spacecraft observations. From a comparative planetology point of view, detailed observations like those performed by the MEX and MAVEN missions would be very much needed at Venus, another non-magnetic planet with similar atmospheric composition, but larger mass.

5.2 ExoMars Rosalind Franklin Rover: A Quest for Past Life

Aside from the fact that Mars is further away from the Sun and ended up being a relatively small planet, its accretional process and composition were largely similar to those of the Earth and Venus (Albarède 2009; Grazier 2016). The first billion years of Mars history, that is, the period during which the young planet still produced enough internal heat to drive abundant volcanism and hydrothermal activity, is very interesting from the point of view of a possible origin of life. The plausible scenario is that once the outgassed primordial atmosphere cooled down below the critical point of water, as on Earth, most of its water vapour condensed onto the surface to form large bodies of water (Vago et al. 2017). Noachian Mars terrains preserve abundant evidence of running water. However, because 4.0 Ga ago the Sun shone with $\sim$70% of today's luminosity, the planet would have been largely frozen: a vast, white expanse interrupted by plentiful volcanoes and hydrothermal systems surrounded by melted pools. Even if cold, there would have been abundant liquid water flowing under the ice, though, courtesy of the planet's internal heat output. So, if it is true that terrestrial life may have started in association with submarine or subaerial hydrothermal systems, it is likely that similar such local environments would have existed on early Mars.

Mars quickly lost most of its atmosphere because it was too warm for its weak gravitational pull. In contrast, Titan has no problem holding onto its dense gas envelope because it is much colder. For the past 3.5 Ga, the atmosphere of Mars has been so tenuous that UV light and cosmic radiation reach the surface with the following adverse effects for the long-term preservation of chemical biomarkers. Firstly, the UV radiation dose is higher than on our planet and would quickly damage exposed organisms or biomolecules. Secondly, the UV-induced photochemistry results in reactive oxidant species that, when activated, can also destroy chemical biosignatures.

Finally, ionizing radiation penetrates the uppermost meters of the planet' subsurface. This causes a slow degradation process that, operating over many millions of years, can alter organic molecules beyond the detection sensitivity of analytical instruments. The radiation effects are depth-dependent: the material closer to the surface is exposed to higher doses than that buried deeper.

Mindful of all these challenges, in the early 2000's ESA began to work on a mission to search for traces of possible past Martian life. The molecular record of ancient microorganisms, if they ever existed, is likely to have escaped radiation and chemical damage only if trapped in the subsurface for long periods. Studies suggest that a penetration in the range of 2 m is necessary to recover well-preserved organics from the very early history of Mars (Kminek and Bada 2006), assuming there has been some help from additional, recently eroded overburden (Dartnell et al. 2007, 2012; Parnell et al. 2007; Pavlov et al. 2012).

It is worth noting that organic molecules – mostly aromatic – were found in the Cumberland sample by NASA's Curiosity rover (Freissinet et al. 2015). This sample was obtained at the surface. The organics were assumed to have, most likely, a cosmic origin – meteoritic organic infall. However, the more recent detection of alkane fragments in the same sample, reported in Freissinet et al. (2025), is very interesting. It is considered a result of high temperature decarboxylation during pyrolysis of some straight-chain carboxylic acid in the sample. This is the first instance of relatively long alkanes observed on Mars. Although these compounds can also be found in meteoritic abiotic kerogens, they could have biological significance.

The study of martian organic-rich material is bound to be difficult. Whatever possible ancient biosignatures we may think are there must be disentangled from the meteoritic background and the effects of radiation damage (which is reduced at depth). It will be necessary to analyse several samples, with different techniques, obtained from a variety of sites, to establish a compelling body of data that can, perhaps, provide support for a tentative claim.

The ExoMars rover mission has had a long and troubled "gestation". Its launch is now planned for 2028. The rover, named after Rosalind Franklin, is equipped with a 2-m drill (Fig. 8). Using the rover Pasteur payload's instruments, the ExoMars science team will conduct a holistic search for biosignatures, both morphological and chemical, and seek corroborating geological context information (Vago et al. 2017).

To maximize our chances of finding signs of past life, we must target the "sweet spot" in Mars' geological history, the one with highest lateral water connectivity between potential habitats —the early Noachian— and look for large areas preserving evidence of prolonged, low-energy, water-rich environments: the type of location that would have been able to receive, host, and propagate microbes. This is why so much care has been devoted to the selection of a landing site of the right age and mineral composition for the mission's objectives.

Oxia Planum is situated at the eastern margin of the Chryse basin, along the Martian dichotomy border. Dated at 4.0–4.1 Ga, it includes one of the largest (about 2500 km^2) known exposures of phyllosilicates on Mars (Quantin-Nataf et al. 2021). Their accumulation is observed to have occurred prior to the emplacement of a putative delta at the outlet of Coogoon Vallis (Molina et al. 2017) - itself draining from an immense catchment region (Fawdon et al. 2022)— signalling that the clay-bearing deposits formed in a large body of water. If this hypothesis is confirmed, Oxia Planum may provide important leads regarding the possible existence of a boreal sea.

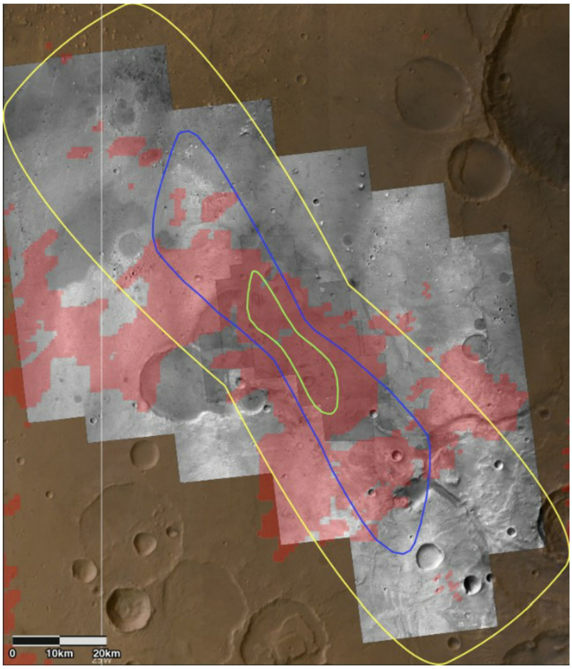


Fig. 9 Oxia Planum landing site for the ExoMars Rosalind Franklin rover. Image layers: 1) Bottom: HRSC pan-sharpened colour mosaic MC11 quadrangle; 2) Middle: CTX orthomosaic (Fawdon et al. 2021); 3) Top: HiRISE ortho- mosaic (Volat et al. 2022). The red overlay indicates phyllosilicate detection by OMEGA. Ellipses: yellow denotes the characterization envelope for landing site study; blue is the 3-sigma ellipse envelope for the 2022 launch opportunity; green is the corresponding 1-sigma ellipse envelope

Approximately 2.5 Ga ago, a resistant, mafic unit, whose wind-eroded remains are still visible today, covered the Noachian paleosurface, offering valuable, long-term protection against ionising radiation effects (Quantin-Nataf et al. 2018).

The Rosalind Franklin rover mission provides a case study of how a wealth of data acquired by instruments aboard Mars Express and partner orbiters: Mars Global Surveyor, Mars Odyssey, Mars Reconnaissance Orbiter and the ExoMars Trace Gas Orbiter; may be used for landing site study, assessment and preparation for science operations. In 2020 a data repository and web Geographic Information System (Calef et al. 2019) were established to house high-level science data products. The HRSC MC11-W mosaic (Figure 1b) served as the base layer to which other layers were georeferenced, and successive remote-sensing products derived from visible, IR, and topographic data were spatially co-registered. The resulting system supported a team-mapping exercise to produce a morpho-stratigraphic map and geologic interpretations (Fawdon et al. 2024; Sefton-Nash et al. 2021) (Fig. 9).

Following the decision to suspend the launch in 2022, the Rosalind Franklin mission is being reformed for a launch with NASA in 2028. ESA is building a new lander and performing some refurbishment work on the rover.

The rover's Pasteur instrumentation remains largely unchanged, with two exceptions. The ISEM IR spectrometer on the mast has been replaced with a new IR spectrometer, Enfys. The neutron detector has been disembarked.

The "new" mission will target the same landing site in Oxia Planum. However, the arrival ellipses, size and azimuths are different for the 2028 launch opportunities. Two possible trajectories have been identified. In either case, the mission will fly a two-year path to ensure that the landing takes place at the beginning of the northern hemisphere's spring. This will result in a dust-free atmosphere and ample sunlight for the rover's solar cells.

Summarising, the interest of the ExoMars Rosalind Franklin mission is predicated on three aspects: 1) the scientific qualities of the landing site, the oldest that we know of, preserving minerals formed in the presence of abundant liquid water; 2) the drill to access and collect subsurface material for the first time; and 3) a next-generation payload able to bypass some of the oxidant problems that have plagued past missions' ability to study organic molecules. This mission will likely turn a new page in terms of chemical composition analysis. If, as we think, the subsurface holds the answer for gaining access to well-preserved organics, our results may well inform the requirements for missions returning samples from the surface of Mars.

5.3 JAXA Martian Moons eXploration (MMX) Mission

The JAXA Martian Moons eXploration (MMX) mission (Kuramoto et al. 2022) will investigate the origin of Phobos and Deimos, study the environment around Mars, and in 2029 return >10 g of sample material from Phobos to Earth for analysis in terrestrial laboratories. The sample mass will be collected by gas-pressure-based and core-sampling systems. MMX will also deploy a rover (Michel et al. 2022) based on the MASCOT rover from Hayabusa 2.

A collaboration between the Mars Express and MMX science teams to support landing and sampling site characterization, and by identifying and organising targeted observations of Phobos. These leverage Mars Express' unique orbit, in which it frequently performs close-distance flybys of Phobos, occurring in flyby "seasons" every 5-6 months, each comprising 4 to 5 flybys with closest approaches between 50 km and 1000 km. This range of flyby distances enables observations of the moon by most of the instruments. In addition to supporting the landing site assessment, MEX data also serve to refine the knowledge of Phobos' ephemeris, shape and gravity field. Furthermore, the collaboration includes coordinated or simultaneous observation campaigns, potentially including: 1) dedicated remote sensing science observations in coordination with MMX before and after landing during Mars Express Phobos flyby campaigns, including support during approach and landing phases and/or after sample collection, 2) coordinated study of Phobos' internal structure from MMX with MARSIS radar sounding investigations, 3) particle instrument observations, to contribute to a better understanding of plasma interactions with Phobos, and 4) coordinated global observations of Mars' atmosphere, focusing on water and dust aerosols, by the Mars Express and MMX spacecraft.

5.4 Expectations from NASA-ESA Mars Sample Return

Technological advances in spacecraft and science instrumentation have increased the quality and volume of data acquired via remote sensing and in-situ investigations. One specific example of a Mars Express contribution that has provided ground-breaking new insights into early Mars science is the revelation by the OMEGA instrument of the global distribution of phyllosilicate minerals (*e.g.*, Carter et al. 2013, 2025, this collection; Bibring et al. 2025, this collection) that sparked interest on further investigating clay-bearing rocks at landing site candidates such as Oxia Planum (Mandon et al. 2021; Quantin-Nataf et al. 2021) and Mawrth Vallis (Poulet et al. 2020) as a means to probe the most habitable period in Mars' past.

Nonetheless, limitations remain to the breadth and depth of science that can be achieved via remote sensing from orbit. For instance, the challenges to resolve features at small spatial scales, or retrieve detailed characteristics of the subsurface. Lander and rover missions with capabilities to collect and analyse samples *in situ* can address these limitations to some degree, but are restricted in their capacity to deliver and operate the most sophisticated instrumentation.

In contrast, terrestrial laboratories offer the possibility to leverage the most performant instrumentation for the study of samples, for many decades, as demonstrated with the Apollo Moon samples. Furthermore, science instrumentation in analytical laboratories on Earth benefits from availability of expert staff, consumables, maintenance and upgradability, as well as from specialised sample preparation techniques. Importantly, samples that are returned to Earth for analysis experience an increase in their scientific potential with time —as a result of innovations in techniques and instruments, but also due to the successive novelty of proposals for opportunistic science investigations.

For these compelling reasons, several decades' worth of scientific community and agency reports have advocated for collecting and bringing to Earth, well-selected Mars samples to pursue scientific objectives that can best be addressed by analysing samples in terrestrial laboratories (Beaty et al. 2019; Haltigin et al. 2018; McLennan et al. 2012; Meyer et al. 2022). The most recent iterations of such objectives (Kminek et al. 2024) were adopted by ESA and NASA efforts in planning a joint Mars Sample Return (MSR) campaign.

As part of this campaign a 'Sample Receiving Project' (SRP) would complement the flight missions to return the samples and would implement the ground elements, including: ground recovery of the returned capsule, sample receiving in a dedicated facility, sample characterization, sample safety assessment, and science analysis. SRP would support detailed scientific studies for advancing our understanding of the geological and astrobiological history of Mars. Investigations would utilise a broad array of advanced laboratory instruments and sample preparation methods that are impossible to achieve with *in situ* robotic missions. Such analyses will probe chemical composition and diversity, will examine small-scale features from known geologic contexts at higher sensitivity, lower detection limits, and finer spatial resolution than ever before.

At summary level, the MSR scientific objectives established for a joint NASA-ESA Mars Sample Return are: (1) to reconstruct the formation and alteration history of the returned samples to understand geological processes and environments of Mars; (2) to determine the astrobiological significance of the martian geological record represented by the samples; (3) to provide new insights into planetary-scale formation and evolution of the inner Solar System and; (4) to identify and characterize potential risks and opportunities for future human missions (Kminek et al. 2024).

The 45-km diameter Jezero impact crater, just north of Syrtis Basin, was selected as the landing site of the Mars-2020 mission, at which samples for return to Earth are collected by the Perseverance rover (Beaty et al. 2019). Jezero has been interpreted as a Noachian open-basin paleolake. It contains several lacustrine deltas and fans fed by a large watershed that was active in the late Noachian. Fluvial processes formed a large delta with diverse water alteration minerals. Carbonate spectral signatures, present along the margin of the crater, suggest they may be lacustrine deposits. The Perseverance rover's exploration of Jezero crater, including its objective to identify and collect samples for future return to Earth, has revealed a surprisingly high diversity of geologic materials and yielded remarkable scientific potential interpreted in the samples collected (Herd et al. 2025).

The NASA-ESA MSR architecture studied consists of three flight missions and the ground-based Sample Receiving Project. The three flight missions begin with (1) the Mars-2020 (Perseverance) sample-collecting rover mission, followed by (2) a Sample Retrieval Lander (SRL) mission, designed to transfer samples to a sealed container aboard a Mars Ascent Vehicle (MAV) that would deliver samples from the surface into Martian orbit. Finally, (3) a rendezvous mission (Earth Return Orbiter, ERO) would perform the round trip to capture and return to Earth the samples delivered by the MAV to Martian orbit.

The Sample Receiving Project would include, as a principle component, the Sample Receiving Facility (SRF) (Carrier et al. 2022). The SRF is necessary to house sample receiving and analysis activities and has two essential overall functionalities:

(1) biocontainment of Martian returned material, until deemed safe for transfer outside the contained facility. This is required for accordance with COSPAR planetary protection policy, that material returned from the surface of Mars should be treated as Category 5 'Restricted Earth-return';

(2) preservation of the scientific integrity of the samples and accommodation of infrastructure and instrumentation to perform scientific measurements for completion of the established science objectives.

After completion of a 'Sample Safety Assessment Protocol' (SSAP), sample characterisation and essential science that is unable to be performed outside SRF, for reasons of time-sensitivity or otherwise (e.g. Sefton-Nash et al. 2025), samples would be permitted for transfer to facilities or laboratories outside the SRF, including for long-term storage and curation, and for analysis in external institutes. Samples would be studied in investigations as a result of successful proposals for objective or opportunity-driven scientific investigations.

The Perseverance Rover formed a first sample "depot" in March 2023. Ten sample tubes were placed at a location named 'Three Forks' for possible future collection and return to Earth. The cache was evaluated according to the MSR science objectives to be Scientifically Return Worthy (SRW) (Czaja et al. 2023). While the 'Three Forks' depot provides a compelling suite of samples for analysis on Earth that would meet the MSR science objectives, the nominal cache of samples collected to remain aboard Perseverance are even more compelling, and includes deltaic sedimentary rocks with high potential to preserve signatures of the ancient fluvial environment at Jezero crater (Stack et al. 2020), and organic molecules. At the time of writing this collection effort continues by the Perseverance rover after it successfully ascended the Jezero delta in December 2024, reaching the western crater rim to explore terrain thought to contain Noachian-aged material pre-dating the formation of Jezero crater.

6 Prospective Studies and Future Mission Concepts at ESA

The Mars ExPeRT (Exploration Preparation, Research and Technology) team is part of ESA's European Exploration Envelope Programme (E3P). It integrates, coordinates, and manages the development of studies and technologies for future Exploration missions to Mars destinations. The Mars Exploration Studies Team oversees mission feasibility and system definition studies for all Mars exploration activities.

A set of exciting and ambitious goals for Mars exploration in the post-MSR era have been outlined in ESA's Terrae Novae 2030+ Strategy Roadmap (ESA 2022) and in the associated Explore 2040 strategy (ESA 2025). The plans have a focus on robotic precursor missions addressing strategic knowledge gaps and developing capabilities to prepare Europe for being part of the first human mission to Mars. Potential new mission concepts for orbital and landed missions have been studied or proposed as part of the planning process.

6.1 ESA LightShip Propulsive Tug with Mars Communication and Navigation Infrastructure (MARCONI) Payload-Delivering Passenger Spacecraft to Mars

Mars is a more costly destination to explore than the Moon. Mars missions require expensive and power "hungry" communications systems to relay data across the large distance to Earth.

Fig. 10 Artist impression of the LightShip Propulsive Tug releasing a Passenger Spacecraft

They also require large propulsion systems. Historically, each Mars orbiter has embarked its own direct-to-Earth communications system and transfers to Mars using a bespoke propulsion system. However, if some of these capabilities could be provided by Mars-established infrastructure, this would allow sending and operating lower-cost spacecraft at Mars.

While the interest in Mars is increasing plans for Mars exploration are being developed in Europe, USA, Japan, China, India and other countries. This means that the demand for data return from Mars will grow. The current communications capabilities do not support the future needs, both in data capacity and temporal coverage, and with an aging population of data relay orbiters at Mars, preparations for the next generation relay infrastructure must begin now.

As well as supporting traditional science data relay from orbit and surface (through X- and K-band radio), optical, direct-to-Earth links are required for really boosting data transmission capabilities in preparation for future human mission needs. Having next-generation communications infrastructure in place would enable future small and low-cost science and technology missions, with no need for large and expensive communications equipment hence enabling higher cadence of small science and exploration missions, increasing science data return and fostering of participation of wider international community. Recently, there has been a growing interest from the global community towards smaller, low-cost Mars mission concepts with focused science or technology objectives.

In addition to the communications services, an in-orbit navigation service will serve to achieve pin-point landing and facilitate autonomous operations. Surface rovers with faster and more regular access to navigation information could move more quickly and safely over the surface, providing faster access to scientific data.

The ESA LightShip Propulsive Tug is a mission concept to provide access to the Mars system as a service to passenger spacecraft (Fig. 10). Every LightShip traveling to Mars would host one MARCONI communications node (which could also be accommodated on other Mars-bound orbiters). After having delivered the passenger spacecraft to their intended orbit, the LightShip would transfer to a MARCONI service orbit from where it can provide high-volume communications and navigation services to Mars users. Thus, the Lightship “tug and talk” service would allow simplifying future missions —providing the opportunity to embark better, more focused scientific payloads— rather than requiring dedicating mass to heavy and expensive propulsion and communications systems.

Over time, an incremental build-up of interoperable LightShip tugs with other Mars-bound spacecraft would reveal the benefits of a network infrastructure, increasing science data relay coverage and volume for orbital and surface users, providing opportunities for Position, Navigation and Timing (PNT) capabilities, and enabling multi-platform science measurements.

Although the LightShip final parking orbital altitude is driven by communications and navigation infrastructure requirements, this kind of network could provide opportunities for atmospheric science, plasma physics, and space weather investigations. The capability for long-term continuous global monitoring with a focused science payload could support developing Mars global weather forecast models, an area in which Europe has a strong expertise.

Passenger spacecraft could be delivered by the tug to a wide range of possible orbits to address a large numerous science and exploration objectives.

6.2 Mars Advanced Entry, Descent and Landing

The Explore 2040 strategy (2024) also proposes a European capability for increased mass and precision landing of future Mars surface missions. To achieve this ambition, Europe must continue to advance in the development of guided entry and precision touchdown technologies.

Following on from the Rosalind Franklin ExoMars Rover, the Mars Advanced Entry Descent and Landing (MEDaL) initiative is the next step in European Mars lander capabilities, aiming to develop a fully European, high precision Mars landing system. An implementation roadmap of increasing precision and mass is envisaged for future missions.

6.3 Small Mars Missions Concepts

Several mission ideas have been studied beyond LightShip and MEDaL, including an orbital and surface weather network, a drilling mission to access subsurface ice, an aerocapture and penetrator mission, and a small satellite science mission.

In the Explore 2040 strategy (2024), small and fast-track missions are highlighted and intended as a regular series of missions offering opportunities for complementary science as well as for focused technology flight demonstrations. Candidate missions such as low-Mars-orbit science missions, aerocapture demonstrators, hard lander/penetrators, small communications and navigation nodes, and high-orbit global monitoring and space weather missions have all been studied or are under study to help prepare for the future.

The LightShip Propulsive Tug would be an ideal capability for taking small and low-cost missions to Mars as well as a platform for larger, more capable spacecraft. A future heavy and precise landing capability would also enable a wide range of robotic surface missions.

6.4 Future Astrobiology

The ExoMars Rosalind Franklin rover will demonstrate the scientific advantages afforded by regional mobility and subsurface access when searching for chemical signs of past life on Mars. Future astrobiology missions should further develop these technologies and implement new ones. Interest is focused on producing the next-generation tools for detecting organic molecules to search for signs of life *in situ*. An area where advances are required concerns the scientific instrumentation used for extracting and analysing organic molecules, particularly if we seek to understand how the biochemistry of potential Martian microorganisms may have differed from that of terrestrial life.

As a next step for science, mass and volume-efficient liquid extraction (using a variety of solvents assisted by focused ultrasound energy) coupled with capillary electrophoresis separation, and possibly with ion-exchange chromatography, is a much less aggressive and performant technique than pyrolysis, presently used in Mars Organic Molecule Analyser (MOMA) on ExoMars. It will grant access to a wider inventory of organic molecules, both polar and non-polar compounds, achieve better sensitivity, and higher yields. Wet extraction minimizes the degradation of target analytes and enables the characterization of non-volatile and large molecules directly in the liquid phase. Improvements to the mass spectrometer design will permit the analysis of both positive and negative ions. The implementation of high-resolution mass spectrometry will facilitate the deconvolution of complex mass spectra, allowing compounds or fragments with the same integer mass but different exact mass, to be discriminated. Crucially, this implies the development of a pressurized, ultraclean, wet-chemistry compartment in the rover's analytical laboratory.

The above-mentioned instruments should be complemented by sets of cameras, spectrometers, and ground penetrating radar such that geological context (top and bottom) can be established to support site interpretation, sample collection and analysis.

7 Conclusions

The past two decades have been a veritable "golden age" for Mars exploration. Many spacecraft have visited the planet, operating both in orbit and on the surface. Undoubtedly, Mars Express can be considered a shining beacon among ESA planetary missions. This relatively small low cost spacecraft has made numerous, profound discoveries, whilst delivering uninterrupted global, multi-disciplinary information for more than two decades.

Mars Express has provided us with new and fundamental knowledge about Mars' early history and by extension, informed that of Earth and Venus, revealing complex geology, the main stages of planet and climate evolution, key processes that shape the Martian atmosphere and ionosphere as well as physics of the plasma environment and escape. Mars Express played an essential role in these investigations, and in those performed by other spacecraft, by virtue of its powerful, multidisciplinary payload suite, long mission duration, and its highly elliptical, non-sun-synchronous, polar orbit. Mars Express is a wonderful example of how a low-cost and fast-track mission can pack impressive science performance and operational flexibility to achieve great objectives. Its implementation, discoveries, and operational history provide many lessons to be learned and applied in future.

Achievements of the early Mars missions and their associated scientific advances has led to a strategy shift from survey oriented to exploration. Future Mars missions will focus on deciphering details of various processes, and most importantly, search for past and present life. The breakthrough is expected from the new generation of rovers with drilling capabilities and *in situ* sophisticated sample analysis.

The next step will be returning samples from Mars to enable precise analysis of their structure, morphology, and composition in dedicated ground-based laboratories. These efforts will pave the way, both technologically and scientifically, for human exploration of the Red Planet.

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Declarations

Competing Interests The authors declare that they have no competing interests.

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