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OVERVIEW

Mars Express: Summary of Scientific Results

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Mars Express is the first European mission to another planet. It has opened the way to further European exploration of Mars with the ExoMars rover and, one day, with a network of surface stations in preparation for the international Mars Sample Return mission. The Mars Express spacecraft has been orbiting the Red Planet for more than five years, during which time it has investigated many scientific aspects of Mars in unprecedented detail, which are summarised in this chapter. Mars Express has revolutionised our understanding of the planet's geological evolution, allowing us to build a comprehensive and multidisciplinary view of Mars, including the surface geology and mineralogy, the subsurface structure, the state of the interior, the climate's evolution, the atmospheric dynamics, composition and escape, the aeronomy and the ionospheric structure. Major advances have been made through discoveries such as the very recent (in geological timescales) occurrence of volcanic and glacial processes, the presence of water ice below the surface and the fine structure of the polar caps. The various types of ice in the polar regions have been mapped, and the history of water abundance on the surface of Mars has been determined in view of the alteration minerals formed at different epochs. The mission has revealed the unequivocal presence of methane in the atmosphere, the existence of nightglow, mid-latitude auroras above crustal magnetic fields in the southern highlands and very high-altitude CO_2 clouds, as well as the solar wind scavenging of the upper atmosphere down to 270 km altitude and the current rate of atmospheric escape. Detailed studies have been made of the crustal gravity anomalies (and thus the properties of the interior), the surface roughness and the fine structure of the ionosphere. Indeed, the presence of methane, independently confirmed by ground measurements, suggests that either volcanism or biological processes are currently active on Mars. Either way, these breathtaking results have given us an entirely new view of the planet.

1. Introduction

Mars Express has revolutionised our understanding of the planet's geological evolution, in conjunction with the 'ground truth' provided by NASA's rovers. A great wealth of data has been gathered, allowing us to build a comprehensive and multidisciplinary view of Mars, including the surface geology and mineralogy, the subsurface structure, the state of the interior, the climate's evolution, the atmospheric dynamics, composition and escape, the aeronomy and the ionospheric structure. Major advances have been made, such as the discovery of water ice below the surface, mapping of the various types of ice in the polar regions, the history of water abundance on the surface of Mars in view of the minerals formed at different epochs, the presence of methane in the atmosphere, mid-latitude auroras above crustal magnetic fields, and much younger timescales for volcanism and glacial processes. Indeed, the presence of methane, independently confirmed by ground measurements, suggests that either volcanism or biological processes are currently active on Mars.

The Mars Express spacecraft has now been orbiting the Red Planet for more than five years. Its High Resolution Stereo Colour Camera (HRSC) has provided breathtaking views of the planet covering both hemispheres, highlighting the very young glacial and volcanic features, from hundreds of thousands to a few million years old, respectively. The OMEGA infrared mineralogical mapping spectrometer has provided unprecedented maps of H_2O ice and CO_2 ice in the polar regions. It has also shown that the alteration of minerals in the early history of Mars reflect the abundance of liquid water, while the nature of minerals formed later suggest a colder, drier planet with only limited periods of surface water.

Also, high-altitude CO_2 ice clouds have been detected in the equatorial region of Mars. The Planetary Fourier Spectrometer (PFS) has confirmed the presence of methane for the first time from orbit, pointing to current volcanic activity and/or biological processes. The SPICAM ultraviolet and infrared atmospheric spectrometer has provided the first complete vertical profiles of CO_2 density and temperature. It has also discovered the existence of nightglow over the atmosphere's nightside, as well as auroras over mid-latitude regions linked to crustal palaeomagnetic signatures, and very high-altitude CO_2 clouds. The ASPERA energetic neutral atom analyser has found that the solar wind is slowly stripping off the high atmosphere down to 270 km altitude, and has measured the current rate of atmospheric escape. The MaRS radio science experiment has studied the surface roughness by pointing the spacecraft's high-gain antenna at the planet and recording the echoes. Also, the martian interior has been probed by studying the gravity anomalies that affect the orbit, and a transient ionospheric layer due to meteors burning in the atmosphere has been identified. Finally, the MARSIS subsurface sounding radar has recorded strong echoes coming from the surface and the subsurface, allowing the identification of the very fine structure of the polar caps. Radar probing of the ionosphere has revealed a variety of echoes originating in areas of remnant magnetism.

2. Deep Interior and Subsurface

One of the objectives of the Mars Radio Science (MaRS) experiment is to study the temporal and spatial variations of the martian gravity field. Gravity is measured by observing the acceleration of a test mass, which is in this case the Mars Express craft itself. For example, the mass excess of a volcano attracts the spacecraft, while the mass deficit of a large impact crater allows the spacecraft to drift away from Mars. Time variations in the gravity field also disturb the spacecraft's orbit, although in a more complex way. The speed and position of Mars Express can be measured to within a few tens of metres by Earth antennas through the round-trip time and the Doppler frequency shift of the radio signal between Earth and the orbiter. It is then possible to compute precise orbits of Mars Express in order to estimate deviations of the path of the spacecraft with respect to the expected trajectory assuming a reference model of the gravity field. Moreover, flybys above specific targets at the surface of Mars are useful for determining the crustal density and the elastic thickness of the lithosphere. Scientists have focused on the volcanic Tharsis region, for which results point to a high loading density in comparison with the mean density of the martian crust. The trajectory of Mars Express is also disturbed by the mass of the Phobos and Deimos moons, enabling us to refine our estimates of the mass of each moon.

Real imaging of the Mars interior was impossible before Mars Express. Altimetry and radio science data from past NASA missions, as well as Mars Express, have provided indirect information about the internal structure of the planet, but the first ever direct subsurface sounding of any planet has been obtained by MARSIS. This multi-frequency synthetic aperture radar is capable of sounding both ionosphere and subsurface, and of detecting material discontinuities in the subsurface, enabling us to understand the distribution of water, both solid and liquid, in the upper crust. MARSIS has probed the polar layered deposits and investigated them down to their base, at a

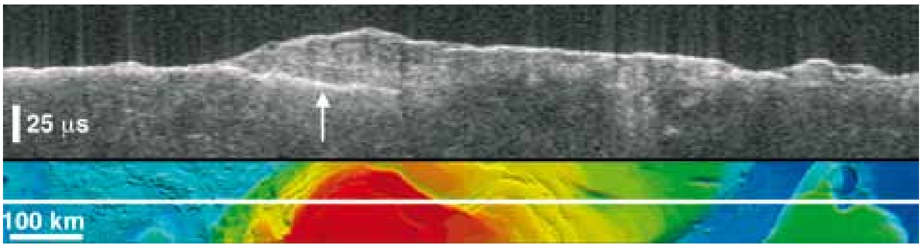

Fig. 1. MARSIS radargram showing water-ice-rich layered deposits below the surface of the southern polar cap. The lower image shows the position of the ground track on a MOLA topographic map (NASA MGS).

depth of several kilometres below the surface (Fig. 1). As a result, we know that the north polar layered deposits are dominated by water ice, with variable amounts of dust. The southern polar cap is more asymmetric, with a maximum ice thickness of 3.7 km. Its interior appears to be almost completely water ice, with little dust. The total amount of water in the southern ice cap is equivalent to a global water layer of 11 m, and thus constitutes an extremely large water reservoir. It also appears that the lithosphere under the southern cap is distorted by the heavy ice.

3. Surface Geology and Mineralogy

Mars was first completely photographed by NASA's Mariner 9 and two Viking orbiters in the 1970s, providing topographic and geological mapping that was used for almost three decades. Since then, only high-resolution but relatively small images have been captured – until Mars Express. HRSC, which consists of a stereo colour imager and a Super-Resolution Channel (SRC), has provided the first large-footprint high-resolution stereo colour images of Mars. HRSC has shed new light on the timing and extent of geological activity (volcanic, fluvial and glacial) from the very early stages more than 4 billion years ago up to the very recent past. Local geological activity is probably still ongoing. A key finding is the very recent activity of some of the large volcanoes. Olympus Mons (Fig. 2), the largest volcanic edifice in the Solar System, is located in Tharsis province, an area that is geologically very young, in some places only 5 million years old. In general, the most recent volcanic activity in both Tharsis and Elysium volcanic provinces was around 100–200 million years ago, which is still geologically very young by martian standards.

Glacial activity on Mars appears to be very recent, and is possibly still continuing in some areas. Ice-related landforms are widespread, extending over very large ranges of latitudes, longitudes and altitudes. Of particular interest is the discovery in tropical and equatorial areas of possible glaciers that were active perhaps only a few million years ago. Apart from the scientific importance of such recent ice-rich deposits and their implications for climate change on Mars, they might still contain ice, and might be accessible by future Mars robotic or human exploration. Among the peculiar landforms discovered by HRSC is a possible recently frozen body of water in Elysium, close to the equator. It is very young – only about 5 million years old. High-resolution, large-swath images from HRSC have made it possible to determine surface ages in unprecedented detail over certain areas. The principle is simple: older surfaces have experienced meteoritic bombardment for a longer time, and therefore contain large numbers of impact craters (Fig. 3).

The high-resolution images over large areas, together with consistent illumination, and matching colour and stereo information, have made it possible to study the geology and to map small areas in much greater detail than in the past (Fig. 4). These images have allowed the geological characterisation of most provinces of volcanic, sedimentary or impact origin on Mars. HRSC imagery is particularly useful for studying sedimentary basins such as fluvio-lacustrine basins, mostly for correlating sediments over large areas (tens or hundreds of kilometres), and provides a very good background for highly detailed observations. Similarly, high-resolution colour images

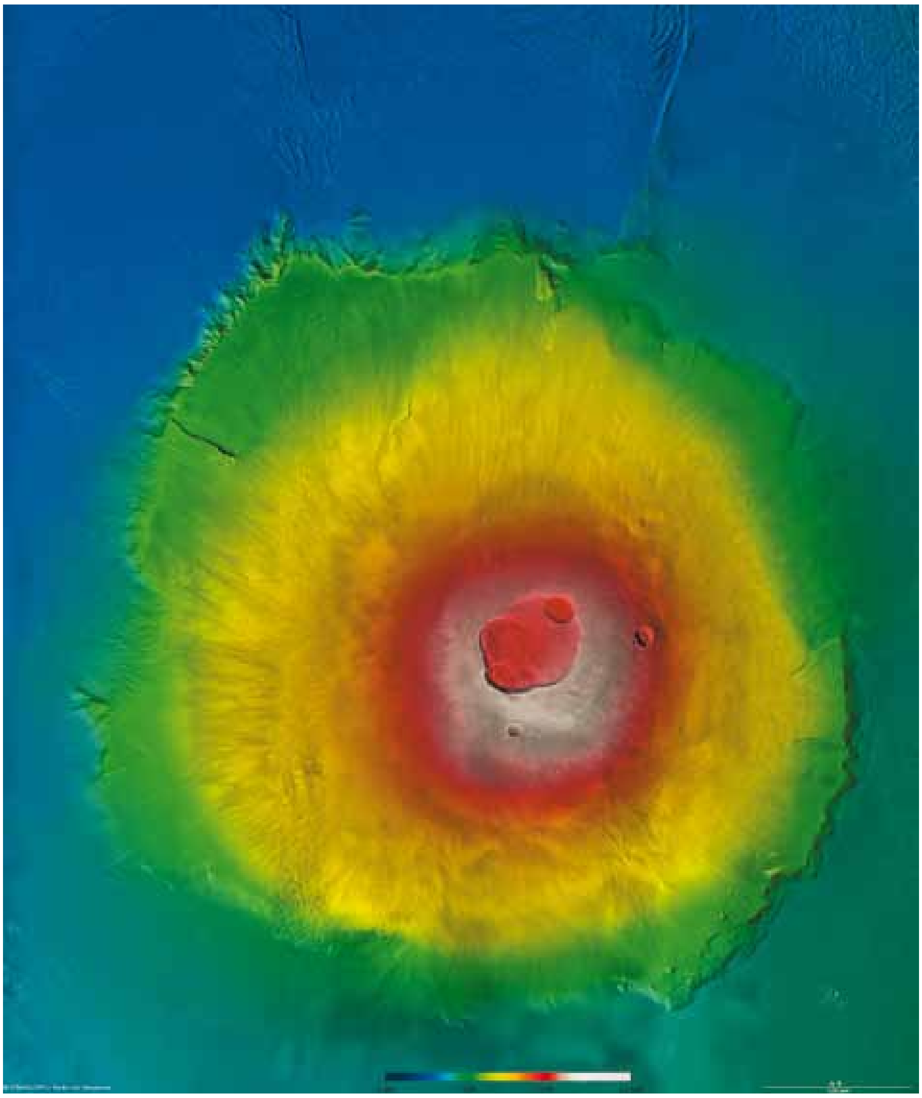

Fig. 2. Olympus Mons (in false colour) as imaged by HRSC, part of a new high-resolution dataset recently released on the internet that allows the visualisation of Mars in 3D.

Fig. 3. Maunder crater, an impact structure 90 km in diameter, located in the Noachis Terra region of the southern hemisphere of Mars, showing barchan dunes similar to those in the African deserts on the crater floor (HRSC).

Fig. 4. Candor Chasma (HRSC view), situated in the northern part of the Valles Marineris canyon system, is one of the many radial grabens formed during the Tharsis uplift that dominated Mars geological history.

provide the basis for a new generation of mapping products. The Viking orbiter images have resolutions of tens to a few hundred metres; HRSC is raising that level by an order of magnitude, adding stereo and colour information. When complete, these images will fill more than 10 000 map sheets at a scale of 1:200 000. No other planned mission will provide comparable wide-swath, high-resolution and global coverage. HRSC is also extremely valuable for future generations of planetary scientists.

Among the many 'firsts' achieved by the mission is the high-resolution hyper-spectral imaging of Mars. OMEGA is a visible/near-infrared hyper-spectral imager that is capable of identifying and mapping atmospheric and surface constituents, including ice and minerals, by their spectral fingerprints. OMEGA has observed both polar caps in detail. The seasonal frost consists mostly of CO_2 ice, while the bulk of layered material is mainly water ice, mixed with dust. There is evidence of hydrated sulphates (gypsum) in the vicinity of the northern polar cap. In the southern polar cap, the 'cryptic region' (a rather dark area during the southern spring) shows the importance of the dust component in this region, which strongly dominates the CO_2 ice. The composition of most of the surface rocks was poorly known, but OMEGA has provided new reliable information. The features and variability of minerals in the crust have been characterised and global maps of pyroxenes have been obtained. Clearly hydrated minerals have been found and mapped. OMEGA has discovered two main classes of hydrated minerals: phyllosilicates (Fig. 5) and sulphates, each with distinct spatial and temporal settings. Phyllosilicates, which are usually formed from the aqueous alteration of volcanic rocks, were discovered in the most ancient outcrops. Hydrated sulphates were discovered in areas mainly in association with thick layered deposits in Valles Marineris, the largest canyon on Mars. All of these occurrences are clearly distinct – most importantly in time – from the ancient phyllosilicates, as the hydrated sulphates are remarkably younger. All these discoveries have provided new and more reliable constraints on the timing and extent of aqueous alteration on Mars,

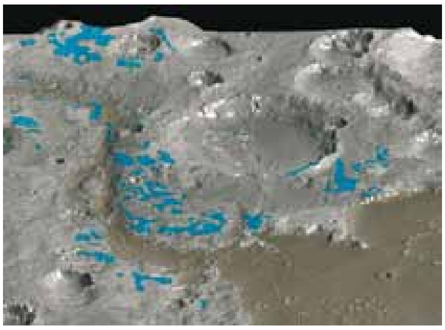

Fig. 5. Clay minerals (phyllosilicates) identified by OMEGA in Mawrth Vallis (20°W, 25°N) formed during long-term exposure to water in the oldest regions of Mars, mapped in blue on an HRSC image.

which has profound implications for reconstructing the evolution of the planet and the search for possible traces of past life.

OMEGA has shown that the perennial ice deposits are of three kinds: water ice mixed with CO_2 ice, patches of water ice tens of kilometres wide, and pure water ice deposits covered by a thin layer of CO_2 ice. The discovery of mixed-ice deposits confirms the long-standing hypothesis that CO_2 acts as a cold trap for water ice. Simulations support the idea that pure water ice deposits are remnants of the planet's orbit precession cycle and formed when the perihelion was synchronised with the northern summer, perhaps more than 10 000 years ago. The deposits of pure water ice migrated back and forth as water vapour (which then condenses and freezes on the surface) between the northern and southern polar caps in a cycle spanning 51 000 years, corresponding to the time when the planet's precession was inverted.

Another important contribution of OMEGA is in complementing the 'ground truth' provided by NASA's rovers investigating the surface composition. OMEGA has given new insights into the surface composition across all terrains of Mars. All other current and future imaging spectrometers are basing their targets and detailed observations on OMEGA's results. Most very high-resolution imaging spectrometers cover only very limited areas in one go, providing very detailed but largely discontinuous coverage, unlike OMEGA. One benefit of the multidisciplinary Mars Express mission is that the instruments can be used in synergy. HRSC and OMEGA provide highly complementary information. This is very important for studies of the poles, given the morphology and colour details from HRSC, the composition information from OMEGA and the 3D slice through more than 3.5 km of ice by MARSIS. The structure and evolution of the polar layered deposits are now known in much greater detail, shedding new light on their composition, volume and dynamics.

4. Atmosphere and Climate

For the first time, SPICAM has mapped the atmospheric ozone (O_3), which absorbs ultraviolet radiation. Ozone-rich areas are found at high latitudes in the northern late winter–early spring period, in the southern autumn and at the end of the northern summer. Water vapour is measured simultaneously with O_3 (another first), which is essential for understanding their relationship. By observing starlight after it has passed through the atmosphere, day and night, vertical profiles of the density and temperature of CO_2 have been obtained for the first time from an orbiter. As CO_2 accounts for most of the atmosphere, these profiles are important in planning for future entry probes. Ozone vertical profiles have also been retrieved, and are used to study concentration variations of this molecule with altitude. SPICAM has reported the highest clouds ever observed on Mars: CO_2 ice clouds have been seen at about 100 km altitude in the southern winter subtropical latitudes, giving new information on cloud formation processes and on atmospheric dynamics.

Certainly, the most intriguing achievement of the PFS is the detection of methane (CH_4). It found a global average mixing ratio of 10 ± 5 parts per billion (ppb) during the first year of observations, with a maximum of 30 ppb, indicating that the concentration of this molecule varies with location. These values can be compared with the atmospheric methane concentrations on Earth and Titan, 1.75 ppb and 5%, respectively. This discovery has led to an intense debate among the scientific community as to where the methane is coming from: life (highly hypothetical) or volcanic activity (although the large volcanoes seem dormant) or some hydrothermal source. Whatever the source, the presence of methane has been confirmed by ground-based telescopic observations. The PFS is also measuring air temperatures from the surface up to about 50 km altitude. Above 60°N, it is cold enough for CO_2 ice to condense; the edge of the northern seasonal polar cap is seen at around 62°N. There is also a clear connection between the surface topography and the thermal structure of the atmosphere. The study of global dust storms is another major objective of the PFS. In July 2007, when a dust storm covered most of the planet, the PFS saw the temperature of the martian atmosphere rise by 20–40°C. As the atmosphere heats up,

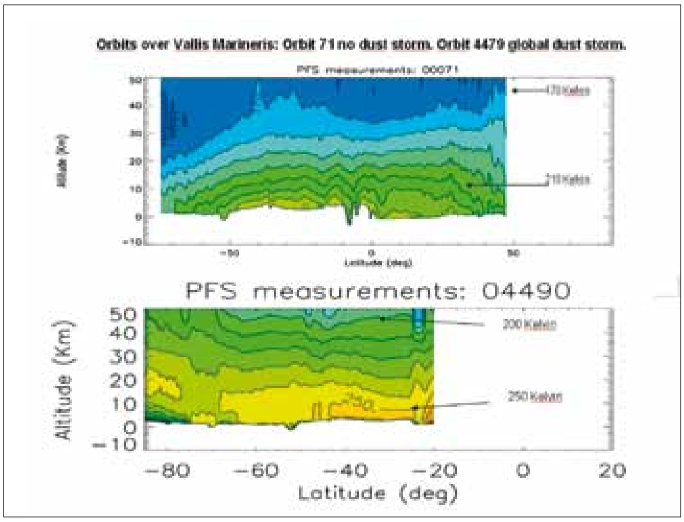

Fig. 6. Temperature variations observed by PFS in July 2007 at various altitudes during a global dust storm over Valles Marineris (bottom), compared with previous measurements without a dust storm (top).

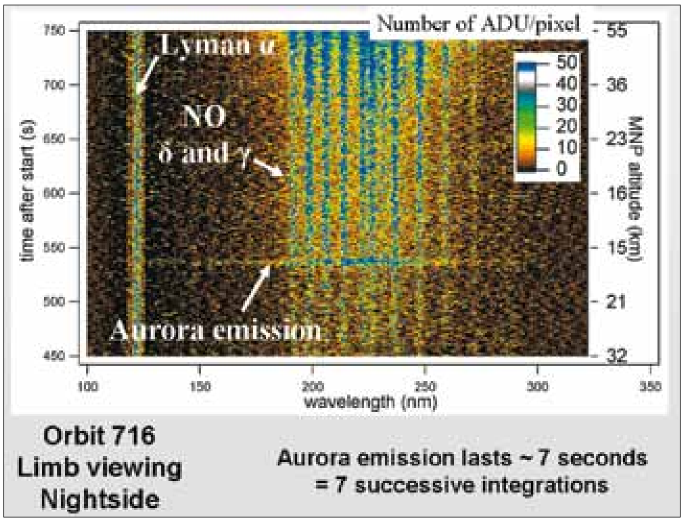

Fig. 7. Auroral emissions observed by SPICAM over mid-latitude crustal magnetic anomalies located in the old cratered highlands of the southern hemisphere of Mars. On Earth, auroras occur at high latitudes, at the 'auroral ovals'.

the atmosphere inflates around the planet. On that occasion (Fig. 6), PFS measured temperatures in the martian atmosphere ranging between –103°C and –63°C at 45 km altitude. However, the temperature increased from –63°C to –23°C at 10 km altitude. Other achievements of the PFS include the identification of minor atmospheric components such as hydrogen fluoride and hydrogen bromide, the detection of water ice clouds, and measurements of the dust content in the atmosphere.

MaRS routinely provides measurements of pressure, temperature and density of the atmosphere, from the surface up to 50 km altitude, for a wide range of latitudes. This broad collection of data is useful for comparison with atmospheric models currently being developed. OMEGA is also providing information on the atmosphere, and new insights into the water cycle of Mars. OMEGA recently detected the presence of CO_2 ice clouds based on a spectral feature around 4.26 µm, which is produced by resonant scattering of solar photons by CO_2 ice particles within a spectral interval dominated by saturated gaseous absorption. Observed clouds exhibit a strong seasonal and geographical dependence, concentrating in the near-equatorial regions during two periods, before and after the northern summer solstice (L_s between 45° and 135°). The simultaneous detection of clouds and their shadows has led to the conclusion that the size of the particles is about 1 µm and that the cloud altitude is above 80 km.

5. Ionosphere

SPICAM has detected two new ultraviolet emissions in the upper atmosphere of Mars. The first comes from nitric oxide (NO) on the nightside, which is an important result to constrain models of atmospheric dynamics, since this emission is produced by NO molecules formed from the recombination of N and O atoms produced on the dayside and transported by the atmospheric circulation to the nightside. The second emission is from molecular nitrogen (N_2), predicted long ago but never observed. SPICAM has also discovered a new kind of aurora, most likely caused by the collision of electrons, diverted by the crustal magnetic field anomalies in the southern hemisphere, with atmospheric molecules (Fig. 7).

As well as studying the subsurface, the MARSIS radar is also probing the ionosphere. Its active sounding mode gives the electron density as a function of altitude. Very interesting shapes of the ionosphere in the areas of the crustal magnetic

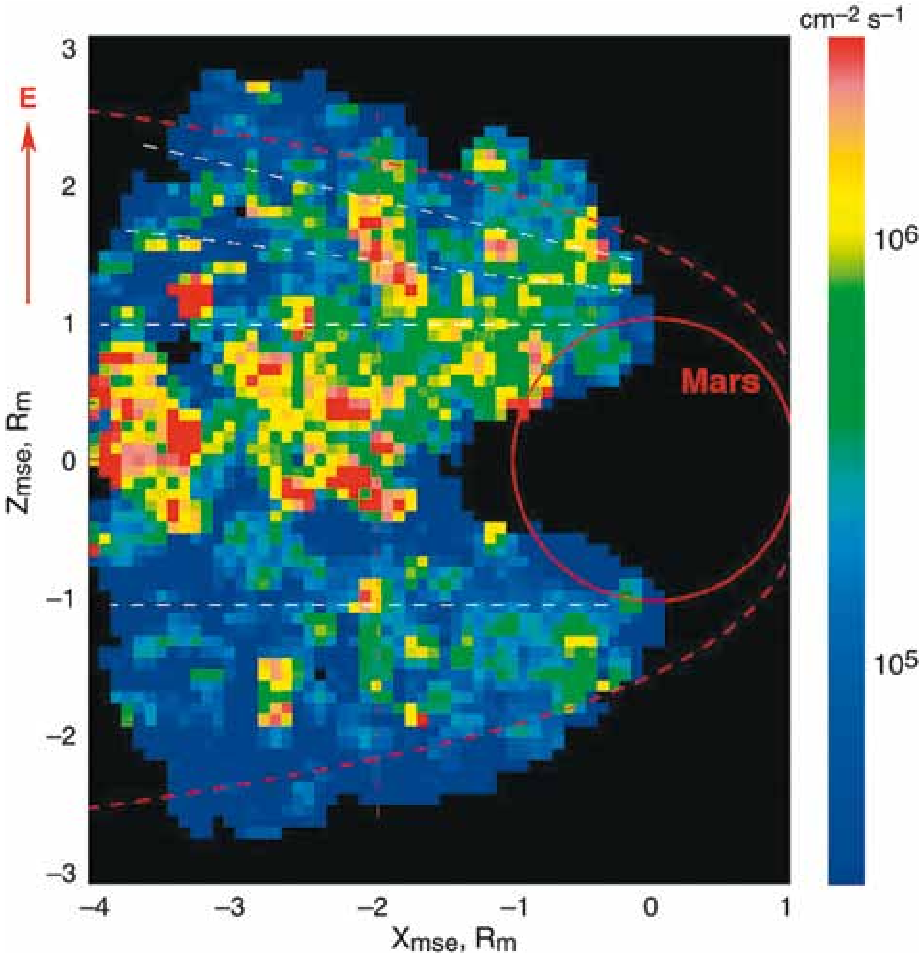

Fig. 8. Atmospheric escape fluxes for the three ions: O^+, O_2^+ and CO_2^+. Mars and the magnetic pile-up boundary (dashed line) are indicated in red.

field have been discovered. In the subsurface sounding mode, the waves reach the surface and the echoes are analysed. The signal is altered by the double pass through the ionosphere, which for the first time gives the total electron content in a planetary atmosphere other than Earth's. In this subsurface mode, the radar signal can be completely absorbed if there are enough free electrons at about 80 km altitude, which tells us about the state of the ionosphere and its variability. The external factors responsible for this variability are in particular the penetration into the atmosphere of energetic solar particles, and possibly solar flares and meteor showers.

The MaRS team routinely derives electron density profiles in the 80–500 km altitude range. How the ionosphere behaves is known from previous NASA missions: a peak in the electron density appears at around 140 km altitude, due to the ionisation of the atmosphere by the solar radiation. The location of the ionopause (the upper boundary of the ionosphere), which is still a matter of debate, has been detected in some profiles at about 350 km altitude. The major result of this experiment is the clear detection of a lower layer, peaking at about 80–90 km. This layer is formed by metallic ions from meteors, exchange reactions between magnesium and iron and molecular oxygen ions, as well as the ionisation of metals by photons.

ASPERA has revealed many new interesting details of the solar wind interaction with Mars. The measurements have shown that the interaction between the solar wind and the atmosphere can be observed all the way down to the lowest point of the spacecraft's orbit (about 250 km altitude) above the dayside. This is quite deep in the ionosphere and the atmosphere. As a consequence, over a period of 3.5 billion years, some 0.2–4 mbar of CO_2 has been lost (Fig. 8). This is not much, indicating that this is not an efficient way for the atmosphere to escape. With its novel technique for measuring energetic neutral atoms (ENAs), ASPERA is exploring a new dimension of the interaction of the solar wind with planets that have no intrinsic magnetic field. Mars is 'shining' in ENAs. Part of this is caused by reflections of inflowing hydrogen ENAs from the solar wind, but a large fraction is emitted when hot plasma, from the solar and planetary winds, interacts with the upper atmosphere to create ENAs.

6. Concluding Remarks

Mars Express has entirely revolutionised our understanding of the planet's geological and climate history. The mission has allowed major discoveries to be made, including the very recent (in geological timescales) occurrence of volcanic and glacial processes, the presence of water ice below the surface and the fine structure of the polar caps. The various types of ice in the polar regions have been mapped, and the past water abundance on the surface has been determined in view of the alteration minerals formed at different epochs. The mission has revealed the unequivocal presence of methane in the atmosphere, the existence of nightglow, mid-latitude auroras above remnant magnetic fields in the southern highlands and very high-altitude CO_2 clouds, as well as the solar wind scavenging of the upper atmosphere down to 270 km altitude and the current rate of atmospheric escape. Detailed studies have been made of the crustal gravity anomalies (and thus the properties of the interior), the surface roughness and the fine structure of the ionosphere.

New techniques used by state-of-the-art instruments have provided the first subsurface radar sounding of another planet, complete atmospheric density and temperature profiles up to 100 km altitude, stellar occultations, total electron content in the ionosphere and surface coverage at high resolution, in both stereo and colour. The coverage will eventually be global provided that the mission is sufficiently extended. The superb images have provided ESA with a significant tool for public outreach, and will also undoubtedly be the legacy of the mission for future generations of planetary scientists as well as the general public.

So far, the various Mars Express experiment teams have published over 250 refereed papers in scientific journals. The scientific data from the nominal mission is now available in the mission archive for further study by the public and scientists alike. The Principal Investigators and their large teams of co-investigators, together with the various ESA teams throughout almost all its establishments, have contributed to the tremendous success of this mission.

The nominal mission lifetime of the orbiter of one martian year (January 2004 to November 2005) has already been extended twice, up to May 2009. The extensions give priority to achieving the remaining goals of the nominal mission (including gravity measurements and seasonal coverage), to catch up with delayed MARSIS observations, and to complete global coverage of high-resolution imaging and spectroscopy. Other goals include subsurface sounding with the radar, observing atmospheric and variable phenomena, and revisiting areas of past discoveries. The scope of cooperation has been broadened, in particular with NASA's Mars rovers Mars Odyssey and Mars Reconnaissance Orbiter, and with Venus Express, which is carrying the same instruments and provides a unique opportunity for comparing our nearest neighbours.

Finally, Mars Express is providing valuable data for preparing two planned missions of ESA's Exploration Programme: ExoMars, which includes a rover for biological, geophysical and climatological investigations, and Mars-NEXT, which includes a network of three or four surface stations complemented by an orbiter for determining the internal structure, the global atmospheric circulation and the geology and geochemistry of the landing sites. In particular, the data from Mars Express are being used to establish a surface/subsurface geosciences database and to refine the existing atmospheric models, in order to identify potential landing sites of high scientific value, and to assess risks during atmospheric entry, descent and landing for the future exploration of Mars.

More detailed information about the Mars Express mission and its wealth of scientific results can be found at *http://sci.esa.int/marsexpress*