Mem. S.A.It. Vol. 82, 321

Memorie della

The exploration of Mars: past and future

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Abstract. In this paper we will describe the main achievement in the Martian exploration, starting from pioneering work of Schiaparelli, and ending with the recent observation obtained by the space mission, from orbit and in situ. Since the time of Schiaparelli observations, Mars become the most interesting object of the Solar system having in common with the Earth several characteristics, such as the presence of geologic phenomena as volcanism and tectonics, and the presence of a thin atmosphere and polar caps. These Martian characteristics are now better understood, also thanks to the "in situ" exploration and this seems to allow us to maintain the hope that - in some areas- Mars could have host a simple life. Among the most important achievements of the Mars exploration should be mentioned the discovery of ices in both polar caps, the identification of Methane in the atmosphere, the existence of extended deposits of sedimentary rocks, including sulphates.

Key words. History and philosophy of astronomy – Astronomical instrumentation, methods and techniques – Space vehicles – Planets and satellites: individual: Mars

1. Introduction

The first observations of Mars were from ground-based telescopes. The history of these observations are marked by the oppositions of Mars, when the planet is closest to Earth and hence is most easily visible, which occur every couple of years. Even more notable are the perihelic oppositions of Mars which occur approximately every 16 years, and are distinguished because Mars is close to perihelion making it even closer to Earth.

In September 1877, (a perihelic opposition of Mars occurred on September 5), Italian astronomer Giovanni Schiaparelli published the first detailed map of Mars. Schiaparelli was born in Savigliano, March 14, 1835. He died in Milan, were he spent the most important pat of its scientific life, July 4, 1910. Since its young age Schiaparelli was part of the international community of astronomers: he went to Berlin in 1854 to study astronomy under Johann F. Encke. Two years later he was appointed assistant observer at the Pulkovo Observatory, Russia, a post he left in 1860 when he was appointed at the Brera Observatory, Milan, where he remained until his retirement in 1900, after becoming director in 1862.

He started observing systematically Mars, in 1877, during a very favourable opposition. At that time, he could start a systematic study of planets, thanks to the installation of a more powerful (8.6-in.) refractor at Brera. He first wanted to test the powers of the new instrument, to see if it "possessed the necessary op-

Send offprint requests to: A. Coradini tical qualities to allow for the study of the surfaces of the planets." The results Schiaparelli's systematic observations was the most detailed map of Mars ever published. With the additional features he filled in over the next decade, it became a standard reference in planetary cartography. Among the different features that he observed, there were the famous "canali". The word, erroneously translated into English as "canals" instead of "channels", led to widespread speculation over whether the "canals" were constructed by intelligent beings (Sagan 1980).

Is the Schiaparelli work still valid? its most important contribution was the first serious attempt to map the surface of another planet. He also started giving to the observed structures original names, derived from Greek and Roman history and mythology. Some of the features that he observed were associated with real features: as an example, a light spot in the southern hemisphere, that he called Nix Olympia it is now known to be the largest volcano in the solar system and re-nominated Olympus Mons. The map that Schiaparelli developed during the first opposition was refined during the opposition of 1879. During its systematic work he also noticed the existence of variable polar caps and the presence of the atmosphere. He interpreted these features correctly, however, he also used these observations in support of the existence of an extended hydraulic system of channels, that unfortunately does not exist.

2. The Mariner and Viking era

2.1. The Mariners

The real improvement in the understanding of Mars was obtained when the space era started. After the successful exploration of the Moon, the interest in applying the navigation techniques developed to reach the Moon to the study of near-by planets was developing. Nowadays we are used, when thinking to a planetary mission, to a complex payload, that includes several sensors able to study different aspects of the surface and atmosphere of a planet at different wavelengths, from X-ray to IR. The first exploratory missions, instead rely mainly on images. So the first observations were a kind of extension of the ground based observations, mainly obtained in the visual range. Early ground-based and spacecraft visible wavelength imaging relied upon photographic techniques, often supplemented by the use of broadband color filters. However, photographic film is a highly nonlinear detector that is extremely difficult to calibrate, so alternatives were sought which allowed for the derivation of more quantitative information from images. A major advance in spacecraft imaging after the film systems of Lunar orbiter was the vidicon, first successfully flown on the Mariner 4 flyby of Mars in 1965 (Leighton et al. 1965). Furthermore, an imaging instrument uses optics such as lenses or mirrors to project an image onto a detector, where it is converted to digital data. At the time of Mariner 4, the detector that creates the image was a vacuum tube resembling a small CRT (cathode-ray tube), called a vidicon. In a vidicon, an electron beam sweeps across a phosphor coating on the glass where the image is focused, and its electrical potential varies slightly in proportion to the levels of light it encounters. This varying potential becomes the basis of the digital video signal produced. Viking, Voyager, and Mariner spacecraft used vidicon-based imaging systems. Early vidicon images (Mariners, 4, 6 and 7) were crude and had low photometric accuracy by today's standards. However, they provided a dramatic first look at Mars. Improved vidicon cameras were extremely reliable with a photometric accuracy generally better than 10% (Mariner 10, Viking, Voyager). The photoconductive surface was sensitive to visible light in a range of about 350 nm to 650 nm. To obtain multispectral data a filter wheel was employed that allowed for several broadband filters typically placed between 400 and 600 nm. Color filters led to the mapping of gross color heterogeneities on a scale of 1-10 kilometers.

Mariner 4 was launched November 28, 1964, on a 228-day mission to Mars. The spacecraft passed Mars at a distance of 9,868 kilometres recording and transmitting to Earth the first close-up picture of the red planet.

In 22 pictures, Mariner's TV camera scanned about one percent of the Martian surface, revealing ancient craters of varying size: that was a big delusion.. was then Mars very similar to the Moon? At any rate the mission completed successfully the first fly-by of Mars. NASA - therefore - decided to perform the first '"dual mission" to Mars. This is a strategy that NASA adopted several times in the Mars exploration: given the difficulty to reach successfully the red planed, the idea was to send two twin spacecraft, to have the guarantee that at least one was able to survive. The twin spacecraft were mariner 6 and 7. The two spacecraft were both launched from Cape Kennedy. The mission's goals were to study the surface and atmosphere of Mars during close flybys, in order to demonstrate and develop technologies required for future Mars missions. Mariner 6 also had the objective of providing experience and data which would be useful in programming the Mariner 7 encounter 5 days later. Unfortunately, both flew over cratered regions and missed both the giant northern volcanoes and the equatorial grand canyon discovered later. Their approach pictures did, however, photograph about 20 percent of the planet's surface, showing the dark features long seen from Earth, but none of the canals observed by Schiaparelli. In total 198 photos were taken and transmitted back to Earth, adding more detail than the earlier mission, Mariner 4. Both spacecraft studied the atmosphere of Mars.

2.2. Mariner 9

The 1971 Mariner Mars mission was again planned to be a dual mission. Unfortunately, the failure of Mariner 8 made it impossible. Mariner 9 then was re-programmed in order to map 70% of the Martian surface and to study the variability of the Martian atmosphere and surface. The novelty of Mariner 9 was that it entered in orbit around Mars, becoming the first artificial satellite of Mars. Launched on May 30, 1971, The orbit was such that the spacecraft circled Mars twice each day for a full year. The payload included a camera, and infrared and ultraviolet instruments. The spacecraft gathered data on the atmospheric composition, density, pressure, and temperature and also the surface composition, temperature, and topography of Mars. At the arrival, Mars was almost totally obscured by dust storms, which lasted for a month. When finally the dust deposited, Mariner 9 revealed the complex geology of Mars, characterized by the presence of one that largest volcanoes of the Solar system and a grand canyon stretching 4,800 kilometres across its surface, roughly parallel to the equator. In honour of Mariner 9 this canyon was named "Valles Marineris" Apparently ancient riverbeds were present but totally dry. Mariner 9 provided the first complete photo-mapping (about 100 percent of the planet's surface) made the first close-up photographs of the Martian moons, Deimos and Phobos.

2.3. Viking orbiters and landers search for life

The Viking Mission to Mars was composed of two spacecraft, Viking 1 and Viking 2, each consisting of an orbiter and a lander. The primary mission goals were to gather high resolution images of the Martian surface, characterize the structure and composition of the atmosphere and surface, and search for evidence of life.The Orbiters imaged the entire surface of Mars at a resolution of 150 to 300 meters, and selected areas at 8 meters.The Orbiter images have been converted to digital image mosaics and maps, allowing the first geological interpretation of the geologic evolution of the surface.

The two lander, instead, were specifically equipped to identify existing life. Viking 1 was launched on August 20, 1975. On July 20, 1976 the Viking 1 Lander separated from the Orbiter and touched down at Chryse Planitia. The landing was successful, despite the fact that both areas, very flat when seen from orbit, was instead, characterized by the presence of large boulders. Viking 2 was launched September 9, 1975 and entered Mars orbit on August 7, 1976. The Viking 2 Lander touched down at Utopia Planitia on September 3, 1976. The Viking Landers transmitted images of the surface, took surface samples and analysed them for composition and signs of life, studied atmospheric composition and meteorology, and deployed seismometers.

The two Viking landers each carried four types of biological experiments to the surface of Mars in the late 1970s. The landers used a robotic arm to put soil samples into sealed test containers on the craft. The two landers were identical, so the same tests were carried out at two places on Mars' surface, Viking 1 near the equator and Viking 2 far enough north to see frost in winter. The experiment specially devoted to the life were: Gas chromatograph - Mass spectrometer (GCMS). This instrument was able to detect several molecules, including organic ones. However the quantity of organic molecules detected was very limited. Gas exchange experiment (GEX)was devoted to see if there were indication of metabolism when adding water to the Martian soil. Also this experiment gave negative results. The Labeled Release (LR) experiment gave somehow ambiguous results. In the LR experiment,on a sample of Martian soil was damped with a drop of very dilute aqueous nutrient solution, inoculated. The nutrients were tagged with radioactive ^{14}C. Then the evolution of ^{14}C in the air above the soil was monitored.The air above the soil was monitored for the evolution of radioactive $^{14}CO_2$ gas in order to see if the was an indication that micro-organisms in the soil had metabolised one or more of the nutrients. The results seem to indicate that a stream of radioactive gases were released by the soil immediately following the first injection.Unfortunately the subsequent injections did not confirm the results. So also this experiment was considered inconclusive. Finally the Pyrolytic Release was based on a similar concept: the Martian soil was exposed to light, water and CO atmosphere. The CO gases were made with ^{14}C, as in the previous experiment. If there were organisms able to operate the photosynthesis, they would incorporate some of the carbon as plants and cyanobacteria on Earth do. Some activity was detected, but it was interpreted as chemical one. The conclusions were that - at least with this kind of instruments - no life was detected.

2.4. A new image of Mars

At the end of this intense period, in which several probes investigated the red planet a new image of Mars emerged. First of all Mars is characterized by an extended crustal dichotomy. The problem of Martian dichotomy was not solved in that period, but only posed. The Martian dichotomy is a global feature separating the cratered southern highlands and smooth northern lowlands. Parts of the boundary are defined by steep slopes with elevation differences of 2-6 km. Older theories foreseen the presence of a giant impact (Wilhelms & Squyres 1984), or impacts. Arguments against are that the geology of the northern lowlands (Vastitas Borealis) is not consistent with a one impact hypothesis (Frey & Schultz 1988). Moreover, the lowlands are not radial in shape (Smith et al. 1999), and there is no evidence of a crater rim. To achieve this results was needed the use of laser altimeter, that permitted to define the Martian topography. The Mars Orbiter Laser Altimeter (MOLA), an instrument on the Mars Global Surveyor spacecraft, has measured the topography, surface roughness, and 1.064-μm reflectivity of Mars and the heights of volatile and dust clouds (Smith et al. 2001). Another possible explanation was that the northern plains were generated by the erosion of an ancient shallow ocean. Topographic profiles across the Mars dichotomy are not consistent with ancient shoreline (Withers & Neumann 2001). Possible shoreline slopes are not orientated in the correct direction. Therefore these shorelines were most likely created by compressive tectonic stress.

The differences between the Northern and Southern hemisphere's can be interpreted using analogues to Earth's plate tectonics. Sea floor spreading continuously forms new crust at rift margins and a new crust will be smother and thinner then old crust. Possibly, subduction destroys the new crust, which provides the energy and material needed for volcanic activity. This could be the Tharsis origin. Convergence will produce contraction features along the "plate boundary". Due to the smooth nature of the northern lowlands "sea floor spreading" must have occurred relatively fast. A quantitative estimate of a full plate spreading rate is 80 mm/yr. The northern lowland crust would have formed rather quickly, and plate tectonics may not have lasted that long. Plate tectonics could aid in cooling the interior of Mars, being generated by convective motion in the interior. Therefore, the interpretation of this dichotomy is related to the thermal history of the planet. Recently (Guest & Smrekar 2005) modeled of the relaxation of the crust locally, taking into account of an internal thermal history assuming convection in presence of a "stagnant-lid" model of the interior. If so, the steep slopes are the product of faulting due to the relaxation of the boundary by lower crustal flow. This relaxation requires that the lower crust must be at least 10 km thick and have a viscosity of $\approx 10^{21}$ Pa s during the first 100-300 Myr of relaxation.

2.5. Volcanism

The Northern Hemisphere is also characterized by an extended volcanism, by the sign of a past extended tectonic activity, that was generating the largest rift in the solar System named "Valles Marineris" . The extended volcanism produced large volcanoes, arranged in sequences, as seen on the Earth in the Hawaiian islands.

The volcanic features on Mars are very similar in shape, but not in dimensions, to those found on Earth, and they probably formed by similar processes. Martian volcanism extended for a large time-span and the volcanoes were generated on terrains of variable ages. Numerous volcanic landforms can be found in the older cratered highlands and in the younger volcanic plains surrounding them. However, the most impressive volcanic landforms are associated with the extensive, hotspot-related uplifts of Tharsis and Elysium plateaus.

The large scale of the Tharsis shield volcanoes suggests that they formed from massive eruptions of fluid basalt over prolonged periods of time. Similar eruptions on Earth are associated with flood basalt provinces and mantle hotspots. However, on Earth the source region for hotspot volcanism moves in respect to the crust, due to the plate tectonics. On Mars an extensive plate tectonics never developed, and we speak now, about a "one-plate" tectonics. Therefore, the Martian surface remains above the plume source so that huge volumes of lava will erupt from a single central vent over many millions of years of activity. A single shield volcano of enormous volume is then generated. The most spectacular volcanic features on Mars are the isolated, giant basaltic shield volcanoes called Montes. The largest of these are four giant shield volcanoes associated with Tharsis uplifted region The largest of the four is Olympus Mons, the largest volcano in the solar system, with a base diameter of 600 km and 25 km of relief from the summit to the plains surrounding it abrupt basalt scarp.

Smaller volcanoes are called Tholi and Peterae characterized by smaller volcanic vents. A Tholus volcano is an isolated mountain with a central crater,and a Patera volcano is dominated by an irregular or complex caldera with scalloped edges, surrounded by very gentle slopes.

At present, the processes that gave rise to the volcanism are not any more active. Only locally, and at small scale, volcanism could be still present. This is very important for the search of life, since the presence of hydrothermal volcanism, some micro-organism could survive.

Geomorphic features visible in orbital images obtained during the Viking missions of the late as well as the infrared spectral data obtained from the floors of rifted basins, or on Mars are suggestive of hydrothermal activity. OMEGA (the IR Mapping Spectrometer of Mars Express) data have permitted to identify deposits of sulphates, indicative of past hydrothermal processes on Mars. Another evidence for hydrothermal activity on Mars derives from studies of SNC meteorites, objects believed to have come from Mars. SNC meteorites comprise a geochemically and isotopically related group of objects that have bulk compositions similar to terrestrial basalts (Newsom et al. 1999). In these meteorites, are present minerals of primary hydrous ,including amphiboles and micas contained within glassy of primary igneous origin, as well as post-crystallization mino-, sulfates, carbonates,halides and ferric oxides formed through interactions with late-stage aqueous. solutions.

2.6. Tectonics

The formation of large volcanic edifices has produced also a large tectonic activity. This was probably produced by mantle processes such as solid-state mantle convection. Because of the large-scale up-warping at Tharsis, fracture systems either radial or concentric to the Tharsis bulge have been identified. This is a network of interconnected grabens centred on the non-volcanic part of the Tharsis uplift and next to the western edge of the Valles Marineris. It is clear that the older, north-trending fractures were overlaid by the younger, more chaotic system. Lithospheric deformation models show that loading over the scale of Tharsis (large relative to the radius of the planet) produces the concentric extensional stresses around the periphery and the radial compressional stresses closer in that are needed to explain the radial grabens and rifts and concentric wrinkle ridges. According to Golombek (2005) models based on present day gravity and topography can explain the observed distribution and strain of radial and concentric tectonic features, implying that the basic lithospheric structure of Tharsis has probably changed little since 3.7 Ga. This Tharsis load appears to have produced a flexural moat around it, which shows up most dramatically as a negative gravity ring (ibid). Many ancient fluvial valley networks, which likely formed during an early wetter and likely warmer period on Mars, flowed down the present large-scale topographic gradient, further arguing that Tharsis loading was very early. If the load is composed of magmatic products as suggested by fine layers within Valles Marineris, water released with the magma would be equivalent to a global layer up to 100 m thick, which might have enabled the early warm and wet Martian climate (Golombek et al. (2001), Golombek (2005)). The largest tectonic feature on Mars is Valles Marineris. Recently a new interpretation of Valles Marineris origin has been proposed by Montgomery et al. (2009). They conclude that the generally linear chasmata of Valles Marineris reflect extension, collapse, and excavation along fractures radial to Tharsis, either forming or reactivated as part of one lateral margin of the Thaumasia gravity-spreading system. The compressional mountain belt defined by the Coprates Rise and Thaumasia Highlands forms the toe of the “mega-slide”. Topographic observations and previous structural analyses reveal evidence for a failed volcanic plume below Syria Planum that could have provided further thermal energy and topographic potential for initiating regional deformation, (ibid). Higher heat flow during Noachian time, or geothermal heating due to burial by Tharsis-derived volcanic rocks, would have contributed to flow of salt deposits, as well as formation of groundwater from melting ice and dewatering of hydrous salts. According with these authors (Montgomery et al. 2009) connection of over-pressured groundwater from aquifers near the base of the detachment through the cryosphere to the Martian surface created the outflow channels of Echus, Coprates, and Juventae chasmata at relatively uniform source elevations along the northern margin of the “mega-slide”, where regional groundwater flow would have been directed toward the surface. This hypothesis provides a unifying framework to explain the relationships between the rise of the Tharsis volcanic province, deformation of the Thaumasia Plateau, and the formation of Valles Marineris and associated outflow channels (Montgomery et al. 2009).

Valles Marineris underwent a complex evolution, due to erosion processes. The Valles Marineris walls in the Tharsis region of Mars have a relief up to 11 km in the central parts of a 4000-km-long system of troughs that lie just south of the Martian equator. Lucchitta (1979) attributes the present configuration of the Valles Marineris walls to erosional scarp retreat, recognizing two major types of walls (Lucchitta et al. 1992): spur-and-gully morphology, landslide scars, and small-scale talus slopes. Gullying probably implies some kind of vertical erosion and longitudinal waste transport by fluids or viscous interstitial material, probably ice Lucchitta (1979), related to the widening of the Central Valles Marineris troughs during the late Hesperian (Lucchitta et al. 1992), and to the emplacement of interior layered deposits.

The relative age of different parts of the Martian surface was estimated through crater counting, as older surfaces have been exposed longer to meteoric bombardment and have thus a higher crater density. Three broad epochs have been identified in the planet's geologic timescale, which were named after places on Mars that belong to those time periods. The precise timing of these periods is not known because there are several competing models describing the rate of meteor fall on Mars (see e.g. Hartmann & Neukum (2001)), so the dates are approximate. From oldest to youngest, these periods are the Noachian epoch (named after Noachis Terra), in which the oldest extant surfaces of Mars formed between 4.6 and 3.5 billion years ago; the Hesperian epoch (named after Hesperia Planum), marked by the formation of extensive lava plains 3.5 to 1.8 billion years ago; and the Amazonian epoch (named after Amazonis Planitia), from 1.8 billion years ago 1.8 to present.

2.7. The polar caps

Mars has two permanent polar ice caps. During a pole's winter, it lies in continuous darkness, chilling the surface and causing 25-30% of the atmosphere to condense out into thick slabs of CO_2 ice (dry ice) (Mellon et al. 2004). When the poles are again exposed to sunlight, the frozen CO_2 sublimes, creating enormous winds that sweep off the poles as fast as 400 km/h. These seasonal actions transport large amounts of dust and water vapour, giving rise to Earth-like frost and large cirrus clouds. Both polar caps show spiral troughs, which are believed to form as a result of differential solar heating, coupled with the sublimation of ice and condensation of water vapour (Pelletier 2004).

2.8. Water on Mars

Viking Orbiters caused a revolution in our ideas about water on Mars by discovering many geological forms that are typically formed from large amounts of water. Huge river valleys were found in many areas. They showed that floods of water broke through dams, carved deep valleys, eroded grooves into bedrock, and traveled thousands of kilometres (Carr 1996). Many craters look as if the impactor fell into mud. When they were formed, ice in the soil may have melted, turned the ground into mud, then the mud flowed across the surface (Carr 1996). Normally, material from an impact goes up, then down. It does not flow across the surface, going around obstacles, as it does on some Martian craters. Regions, called "chaotic terrain", seemed to have quickly lost great volumes of water which caused large channels to form downstream (an example can be seen in Fig. 1). The amount of water involved was almost unthinkable - estimates for some channel flows run to ten thousand times the flow of the Mississippi River (Carr 1996). Underground volcanism may have melted frozen ice; the water then flowed away and the ground just collapsed to leave chaotic terrain.

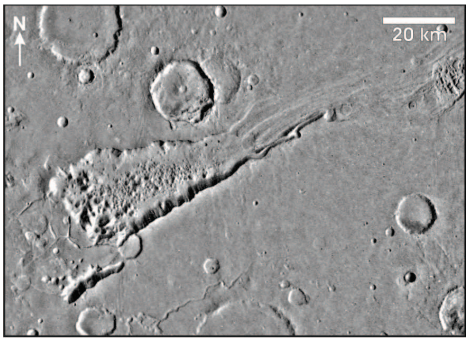

Fig. 1. An example of chaotic terrain and outflow channels in Aromatum Chaos, Mars (1.09°S 317°E). The outflow channel feeds into Hydroates Chaos, ultimately extending onto the plains of Chryse Planitia through Simud Vallis and Tiu Vallis. Illumination is from the right. Viking Mars Digital Image Model mosaic.

Estimates of the amount of water outgassed from Mars, based on the composition of the atmosphere, range from 6 to 160 m, as compared with 3 km for the Earth. In contrast, large flood features, valley networks, and several indicators of ground ice suggest that at least 500 m of water have outgassed (Carr 1987). The two sets of estimates may be reconciled only if early in its history, Mars lost part of its atmosphere by impact erosion and hydrodynamic escape (Carr 1996).

2.9. The atmosphere, past and present

The atmosphere of Mars is relatively thin, and pressure on the surface varies from around 30 Pa on Olympus Mons's peak to over 1,155 Pa in the depths of Hellas Planitia, with a mean surface level pressure of 600 Pa, compared to Earth's sea level average of 101.3 kPa. However, the scale height of the atmosphere is about 11 kilometers, somewhat higher than Earth's 7 kilometers. The atmosphere on Mars consists of 95% carbon dioxide, 3% nitrogen, 1.6% argon (Owen 1992).

The existence of liquid water on the surface of Mars requires both a warmer and thicker atmosphere. Atmospheric pressure on the present day Martian surface only exceeds that of the triple point of water (6.11 hPa) in the lowest elevations; at higher elevations water can exist only in solid or vapor form. Annual mean temperatures at the surface are currently less than 210 K, significantly less than what is needed to sustain liquid water. However, early in its history Mars may have had conditions more conducive to retaining liquid water at the surface.

Early Mars had a carbon dioxide atmosphere similar in thickness to present-day Earth (Carr 1999). Despite a weak early Sun, the greenhouse effect from a thick carbon dioxide atmosphere, if bolstered with small amounts of methane (Squyres & Kasting 1994) or insulating effects of carbon dioxide ice clouds (Forget & Pierrehumbert 1997), would have been sufficient to warm the mean surface temperature to a value above the freezing point of water. The atmosphere has since been reduced by sequestration in the ground in the form of carbonates through weathering (Carr 1999), as well as loss to space through sputtering (an interaction with the solar wind due to the lack of a strong Martian magnetosphere) (Kass & Yung 1995).

3. The latest generation of missions to Mars

For almost twenty years after the Viking mission no probes were sent to Mars, perhaps because of the failure of Viking landers to find any evidence of existing life. Mars Global Surveyor (MGS) was the first successful NASA mission launched to Mars since the Viking mission in 1976, arriving at Mars on September 12, 1997 and operating until November 2006. Perhaps the most important results of MGS is the discovery that liquid water episodically flows over the surface of the planet even today, through release from subterranean reservoirs along sun-facing scarps and cliffs (Malin & Edgett 2000). Although the quantity of water released in this way is very small, compared to that required to carve outflow channels and valley networks, the presence of liquid water implies the potential existence of biological habitats in the Martian subsurface.

Another important finding of MGS is the detection of patches of residual magnetization in the Martian crust (Acuna et al. 1998). This implies that Mars, once, had a magnetic field, and thus an internal dynamo like the Earth, which stopped in the mid-Noachian, about four billion years ago, for causes that are still being debated (Lillis et al. 2008). Without the shielding from the solar wind afforded by the magnetic field, the radiative environment at the surface of the Earth would be too harsh for life, as it is today on Mars, whereas the presence of a magnetic field would have made it possible for life to evolve on a once wetter Mars.

A final discovery of MGS that influenced the exploration strategy for the determination of the biologic potential of Mars is that of a fossilized and exhumed delta, which was formed most likely by the flow of water, in Eberswalde crater (Malin & Edgett 2003). The existence of the delta provides unambiguous evidence that bodies of water existed in the past. Although it is currently deemed that the delta likely formed not in a stable long-lived lake but over the course of a small number of shorter lacustrine episodes (Lewis & Aharonson 2006), Eberswalde crater is one of the potential landing site for NASA's future Mars Science Laboratory rover, whose objective is the search for signs of ancient life.

Following the discoveries made by MGS, NASA's 2001 Mars Odyssey was launched on April 7, 2001, and arrived at Mars on October 24, 2001. It is still in operation, and it is thus the longest-serving spacecraft at Mars. Its mission is to search for evidence of past or present water and volcanic activity. Thanks to the gamma ray spectrometer on board, it was found that the upper layers of Martian soil poleward of 55° of latitude contain up to 50% water ice by weight (Boynton et al. 2002). Because this sensor can analyse only the top meter of soil, it is not known if ice fills available pore space below this depth. It is estimated that total amount of water that could be buried in the soil would be equivalent to a global layer 0.5 to 1.5 km deep (Boynton et al. 2002).

After decades in which Mars exploration was advanced through American probes (while Soviets made many attempts that mostly met failure), the European Space Agency (ESA) launched its first mission to Mars, called Mars Express, on June 2, 2003. Mars Express consists of two parts, the Mars Express Orbiter and the Beagle 2, a lander designed to perform exobiology and geochemistry research. Although the lander failed to land safely on the Martian surface, the Orbiter is successfully performing scientific measurements since early 2004, namely, high-resolution imaging and mineralogical mapping of the surface, radar sounding of the subsurface structure, precise determination of the atmospheric circulation and composition, and study of the interaction of the atmosphere with the interplanetary medium.

The importance of water for both the geologic, climatic and potentially exobiological evolution of Mars was recognized already in Viking times, but after MGS and Mars Odyssey the search for water became one of the key drivers of scientific exploration. From the early mapping observation of the permanent ice caps on the Martian poles, the northern cap was believed to be mainly composed of water ice, whereas the southern cap was thought to be constituted of carbon dioxide ice. The OMEGA spectrometer on board Mars Express achieved the first direct identification and mapping of both carbon dioxide and water ice in the Martian high southern latitudes, showing that this south polar cap contains perennial water ice in extended areas (Bibring et al. 2004).

After OMEGA revealed that the South polar layered deposits of Mars were ice-rich, the MARSIS subsurface sounding radar on Mars Express probed them penetrating to depths of more than 3.7 kilometers. It was found that the characteristics of radar echoes were compatible with a composition of nearly pure water ice down to the bottom of the deposits, beyond what OMEGA could detect. Because MARSIS was able to map the thickness of the layered deposits over the entire South polar area, it was possible to estimate that the total volume of ice contained in them is 1.6×10^6 cubic kilometers, which is equivalent to a global water layer approximately 11 meters thick (Plaut et al. 2007). Although this is below most estimates of the volume of water needed to carve geologic features such as outflow channels and valley networks, it is the largest known reservoir of water on the planet.

Perhaps the most important discovery made by Mars Express is the detection of methane in the atmosphere by the PFS spectrometer (Formisano et al. 2004). Methane is not stable in the Martian atmosphere, because solar UV radiation causes its photodissociation over times of perhaps several centuries. This time is long enough for any release to distribute evenly around the planet, but careful analysis showed that methane was localized in specific areas. Its concentration there increased from Martian spring through summer, then dropped. This argues for destruction by UV-produced peroxides or other rapid chemical oxidants on the surface or entrained on airborne dust. Most importantly, it also indicates real-time release of methane from an active source.

There are only a few processes thought to be able to produce methane on Mars, by analogy with the Earth. Volcanism is one possibility, but there has been no detection of on-going volcanic activity on Mars in spite of many thermal infrared sensors searching for it. Another potential source could be a reaction of olivine rock with groundwater and subsurface heat (serpentinization), but it is unclear if the necessary temperatures can be reached in the Martian subsurface. The third possibility is subterranean microbial life. Because of the immense significance of the discovery of extant life on Mars, the determination of the origin of methane has become the new key driver of scientific exploration, and both NASA's Mars Science Laboratory (to be launched in 2011) and ESA's ExoMars (whose launch is planned for 2018) will carry instruments to detect and analyze Martian methane.

Connected to the problem of the habitability of Mars, OMEGA was able to complete a thorough mapping of the spectral properties of the Martian surface, which led to the identification of hydrated minerals requiring for their formation a much wetter environment than today's Mars. This discovery reinforced the theory that liquid water was present on the Martian surface in the past, and eventually led to the proposal of an alternative timeline for Mars based upon the correlation between the mineralogy and geology of the planet. This proposed timeline divides the history of the planet into three epochs; the Phyllocian, the Theiikian and the Siderikan (Bibring et al. 2006).

- The Phyllocian (named after the clay-rich phyllosilicate minerals that characterize the epoch) lasted from the formation of the planet until around four billion years ago. In order for the phyllosilicates to form an alkaline water environment would have been present.
- The Theiikian (named, in Greek, after the sulfate minerals that were formed), lasting until about 3.5 billion years ago, was a period of volcanic activity. In addition to lava, gases - and in particular sulfur dioxide - were released, combining with water to create sulfates and an acidic environment. The vulcanism era left features indicative of the interaction between water and lava and/or magma on Mars.
- The Siderikan, from 3.5 billion years ago until the present. With the end of volcanism and the absence of liquid water, the most notable geologic process has been the oxidation of the iron-rich rocks by atmospheric peroxides, leading to the red iron oxides that give the planet its familiar color.

The new insight provided by this analysis has led planners of future missions to Mars to the conclusion that deposits from the Phyllocian era are the best candidates to search for evidence of past life on the planet. Although observations from orbit can still contribute to the global characterization of the planet, to test the most exciting hypotheses about the presence of liquid water, and perhaps life, the acquisition of samples for complex and detailed in situ analysis is considered to be essential.

Briefly following Mars Express, NASA's twin Mars Exploration Rovers Spirit and Opportunity launched toward Mars on June 10 and July 7, 2003, landing on Mars January 4 and January 25, 2004. While Spirit has not been communicating with Earth since March 22, 2010, Opportunity is still driving on the surface of Mars. Primary among the mission's scientific goals is to search for and characterize a wide range of rocks and soils that hold clues to past water activity on Mars. The spacecraft were targeted to sites on opposite sides of Mars that appear to have been affected by liquid water in the past. The landing sites are at Gusev Crater, a possible former lake in a giant impact crater, and Meridiani Planum, where mineral deposits (hematite) suggest Mars had a wet past. It was indeed found that, most likely, Meridiani once had abundant acidic groundwater, arid and oxidizing surface conditions, and occasional liquid flow on the surface (Squyres et al. 2006), while the granular rocks found in Gusev, the so-called "blueberries", have been interpreted to be volcanic ash and/or impact ejecta deposits that have been modified by aqueous fluids during and/or after emplacement (Arvidson et al. 2006). These findings add to those obtained from previous missions in outlining an image of Mars' past as a wet environment favourable to the evolution of life, but in the current sterilizing surface conditions (due to intense UV radiation), no evidence of past or present life can be preserved. Future steps in the search for life on Mars will thus require access to the subsurface for in situ analysis.

In the unfolding of NASA's strategy for the exploration of Mars, the next mission was Mars Reconnaissance Orbiter (MRO), which was launched on August 12, 2005, and attained Martian orbit on March 10, 2006. In November 2006, after five months of aerobraking, it entered its final orbit and began its science activity, which still continues today. MRO's scientific goal is to search for evidence that water persisted on the surface of Mars for a long period of time: while other Mars missions have shown that water flowed across the surface in Mars' history, it is still unclear whether water was ever around long enough to provide a habitat for life. Another important goal for MRO is to provide support to lander missions in the form of high-resolution observations of the surface for the detection of landing hazards.

Very high resolution images obtained by MRO revealed fluvial landforms that have been interpreted as the result of sustained precipitation, surface runoff, and fluvial deposition occurring during the Hesperian on the plateaus adjacent to Valles Marineris (Weitz et al. 2010). Thus, liquid water would be present non only in the Noachian but also through the Hesperian, in the form of rain perhaps thanks to an enhanced greenhouse effect from bursts of volcanic activity releasing vast quantities of CO_2 in the atmosphere.

The SHARAD subsurface sounding radar on MRO, endowed with a tenfold-better resolution compared to MARSIS, provided evidence that Mars' climate undergoes dramatic periodic changes and may now be in a warming trend (Phillips et al. 2008). This can be seen in Fig. 2, showing a radar cross-section of Mars' north polar ice cap acquired by SHARAD: ice layering shows rhythmic cycling between bundles of dust-containing layers and interspersed clean ice, reflecting changes in environmental conditions during deposition. The driving force for the climate changes appears to be the large variations in Mars planetary motions. As with Earth, Mars' orbit is eccentric, its rotational axis precesses, and especially, its obliquity (axial tilt) oscillates. At low obliquity, less sunlight falls on polar regions, which accumulate snow. At high obliquity the poles receive more sunlight and the equator less, so snow migrates to equatorial regions. At present the obliquity of Mars is calculated to be roughly 25° and decreasing, indicating that in (geologicly) recent times the axial tilt was substantially larger and ice would be expected near the equator.

In the wake of MRO, the Phoenix lander was launched on August 4, 2007, descending on Mars on May 25, 2008. The mission objective was to search for environments suitable for microbial life on Mars, and to research the history of water there. The lander completed its mission in August 2008, and made a last brief communication with Earth on November 2 as available solar power dropped with the Martian winter. The mission was declared concluded on November 10, 2008, after engineers were unable to re-contact the craft. Phoenix excavated into the upper centimeters of soil to reveal water ice, confirming predictions made by in 2002 by the Mars Odyssey orbiter. It was able to perform accurate chemical analysis of soil samples thanks to its wet chemistry laboratory, revealing the presence of a number of salts, especially perchlorate (Hecht et al. 2009). This salt greatly lowers the freezing point of water, and thus may be allowing small amounts of liquid water to form on Mars today. Furthermore, perchlorate is used as food by some bacteria on Earth through anaerobic reduction.

4. The future

Discoveries described in the previous section have changed the paradigm of Martian geologic evolution that consolidated at the end of the Viking era, reviving the possibility of the presence of life and spurring the development of future missions aimed at finding it. As of today, NASA and ESA are planning a total of four missions to Mars over the next decade, while Russia and Japan have announced their interest in participating. It is becoming increasingly clear that, in sharp contrast to the conquest of the Moon, the future of Mars explo-

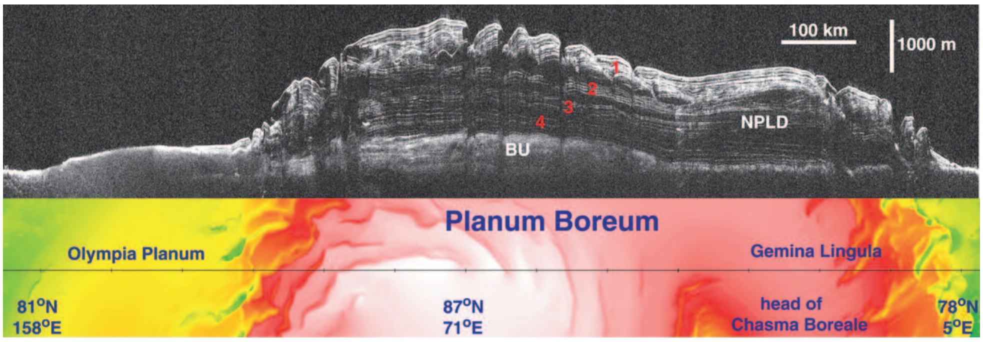

Fig. 2. (Top) Radar cross-section from SHARAD orbit 5192 above Planum Boreum, Mars. The North Polar Layered Deposit geologic unit (NPLD) and the Basal Unit (BU) beneath the NPLD are labeled. Internal radar reflections arise from boundaries between layers differing in their fractions of ice, dust, and sand. The radar reflections in Planum Boreum are clustered into distinct packets of reflectors (numbered). (Bottom) Ground track of orbit 5192 shown on a topographic map of the north polar region of Mars (adapted from Phillips et al. (2008)).

ration will be based on international collaborations involving all space-faring nations in the world.

The next mission to Mars will be NASA's Mars Science Laboratory (MSL), which is scheduled to be launched in November 2011 and land on Mars in August 2012. The MSL rover will be over five times as heavy as and carry over ten times the weight of scientific instruments as the rovers Spirit or Opportunity, and its goal will be to determine whether Mars ever was, or is still today, an environment able to support microbial life (Cabane & SAM Team 2010).

NASA's Mars Atmosphere and Volatile Evolution (MAVEN) is set to launch in the period between November 18 and December 7, 2013, and will explore the planet's upper atmosphere, ionosphere and interactions with the sun and solar wind, to determine the role that loss of volatile compounds - such as carbon dioxide, nitrogen dioxide, and water - from the Mars atmosphere to space has played through time, giving insight into the history of Mars atmosphere and climate, liquid water, and planetary habitability (Jakosky 2009).

ExoMars Trace Gas Orbiter will be the first joint ESA and NASA mission to Mars, a flexible collaborative proposal within NASA and ESA to send a new orbiter-carrier to Mars in 2016 as part of the European-led ExoMars mission. This orbiter will deliver the ExoMars static lander and then proceed to map the sources of methane on Mars and other gases, and in doing so, help select the landing site for the ExoMars rover to be launched on 2018 (ESA 2010a). The ExoMars Rover will, in turn, characterize the biological environment on Mars in preparation for robotic missions and then human exploration (ESA 2010b).

This is thus a very exciting time for Mars exploration, and the current decade will probably revolutionize our understanding of Mars even more than the previous one. Still more important, we will gain precious insight on the way life develops in the Universe, and on the likelihood of the occurrence of life on planets other than the Earth. Ironically, we may well conclude that Schiaparelli's ideas on the presence of life on Mars were not so far off the mark. Certainly, one has to concede that there are channels on Mars, after all.

Acknowledgements. This research has made use of NASA's Astrophysics Data System.

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