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The present and past climates of planet Mars

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Abstract. Mars is a small planet with a thin atmosphere of almost pure carbon dioxide. To first order, the Martian meteorology can be compared with what one would expect on a cold, dry desert-like Earth. However, several phenomena make the Martian climate system more complex than it appears. First, as much as 30% of the carbon dioxide atmosphere condenses every winter at high latitude to form CO_2 ice polar caps, inducing large surface pressure variations all over the planet and an atmospheric circulation without equivalent on Earth. Second, a highly variable amount of suspended dust lifted by the winds modifies the radiative properties of the atmosphere, with sometime global dust storms able to totally shroud the planet. Last, a peculiar water cycle occurs on Mars, with water vapor transported by the atmosphere between the polar caps and possibly subsurface reservoirs, allowing the formation of clouds, hazes and frost. Telescopic and spacecraft observations have shown us that this complex climate system is highly variable, seasonally and from year to year, but these variations remain poorly understood. In fact, the Martian climate system has probably experienced large variations related to the oscillations in the parameters of the orbit and rotation of Mars (obliquity) a few millions or even thousand of years ago. These oscillations affected surface temperatures and the water cycle, inducing the mobilization and accumulation of large ice deposits in various locations on the planets. In a much distant past, it is also likely that Mars may have been a completely different planet. The observations of the geology (dry riverbeds and deltas, lacustrine sediments) and mineralogy (clay, sulfate) of the oldest surface on Mars dating back to more than 3 billions years ago provide evidence that liquid water was then abundant on the surface, at least episodically. Mars may have been warmed by a thicker atmosphere containing greenhouse gas and clouds, high geothermal fluxes, or episodically by large asteroid impacts.

1 Introduction

The particular importance of Mars among the other planets results primarily from the existence of its atmosphere. On the one hand, it endows Mars with a unique "Earth-like planet" status which motivates many studies aimed at testing the concepts, theories and tools developed for Earth climate sciences on a slightly different system. On the other hand, the atmosphere may have enabled the climatic conditions on Mars to have sometime been suitable for liquid water on its surface, and thus life. Mars present-day climate system is complex, highly variable and only partly understood. Mars, however, is cold and dry, and its atmosphere is so thin that the presence of liquid water, never detected, is unlikely on the surface. Nevertheless, the planet was probably different in the past. The surface of Mars is characterized by multiple geological evidences that suggest that liquid water existed at and near the Martian surface at various time in its history. Two concepts of past climate (or "paleoclimate") must be distinguished for Mars. On the one hand, it appears that the climate was sometime different from what it is

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today throughout most of its history and until quite recently on the geological timescale (a few millions ago, or even a few thousands of years ago) because of the oscillations of Mars orbit and rotation parameters. On the other hand, the observation of the geology and mineralogy of the oldest surface on Mars (dating back to more than 3 billion years ago) provide evidence that the Martian climate was then completely different then, with abundant liquid water on the surface, probably because of a thickest atmosphere or a higher geothermal flux.

The purpose of this chapter is to briefly review what we know about the Mars climate and water on the red planet. It is written for students or scientists who may not know anything about Mars and its climate. I first describe the current Martian climate system and our current understanding of the inventory of water reservoirs on present-time Mars. In a second part, I will address the recent variations of Mars climate. Last, I will present why it is believed that Mars early climate was so much different from what is its today.

2 The present Martian climate

Mars is a small planet about half the diameter of the Earth and about one and a half time more distant from the sun. The atmospheric pressure at the surface range from 1 mbar to 14 mbar depending on location and season (compared to 1013 mbar on average at sea level on Earth). The dominant gas is CO_2. In spite of these differences, the Martian climate system is similar to the Earth climate system in many aspects. The two planets rotate with almost the same rate and a similar obliquity. The length of day is thus almost the same (24 h and 40 minutes on Mars) and the seasonal cycle is comparable. In such conditions, the general circulation is controlled by similar processes: On both planet, the Hadley circulation (the process that generate the trade winds) is important at low latitudes, whereas "baroclinic" planetary waves (a succession of low- and high-pressure zones) dominate the weather system at mid-latitudes.

2.1 A "hyper-continental" climate

On a fine afternoon on Mars, in southern summer, the weather may be quite mild: 20 °C, with a gentle trade wind... But with the night come glacial conditions, as temperatures fall by tens of degrees to −100 °C, and remain there until morning. Martian soil is dry and granular, and inefficient at storing heat: its 'thermal inertia' is very low compared with the surface of the Earth, with its oceans. Also, since the atmosphere of Mars is so tenuous, variations are much more marked. Briefly, the climate of Mars is 'hyper-continental'.

One result of this is that the cycle of seasons is much more marked on Mars than on Earth, especially at the two solstices. At these times, both planets are inclined in such a way as to present one pole towards the Sun all day: so the 'summer pole' receives the most solar energy throughout the day. On Earth, the thermal inertia of ice, and of the oceans, and especially the reflection of radiation from ice and snow, ensure that the North Pole is not hotter than, for example, Death Valley. These effects are negligible on Mars, so temperatures (averaged out over the day) are at their highest in the polar region of the summer hemisphere at the solstice. As one moves from the summer pole towards the winter pole, temperatures continuously decrease down to the freezing point of CO_2, the main constituent of the atmosphere (see below). This hemispherical asymmetry is observed most of the time except around the equinoxes where a more Earth-like regime is observed with cold poles and warmer areas around the equator.

In every season, these temperature gradients are the drivers of the circulation of the atmosphere. To first order, the Martian meteorology can thus be compared with what one would expect on a cold, dry desert-like Earth. However, just like the climate system on the Earth is not controlled only by temperature gradients and the atmospheric circulation because of the presence of oceans and water clouds, several phenomena make the climate system more complex on Mars.

First as much as 30% of the carbon dioxide atmosphere condenses every winter at high latitude to form polar caps, inducing surface pressure variations all over the planet (**CO_2 cycle**). Second, a highly variable amount of suspended dust do modify the radiative properties of the atmosphere, with sometime global dust storms totally shrouding the planet (**dust cycle**). Last, a peculiar hydrological cycle occurs on Mars, with water vapour transported by the atmosphere and the formation of clouds, hazes and frost (**water cycle**).

2.2 The CO_2 cycle and the seasonal polar caps

The polar caps are the most apparent aspect of the Martian seasonal cycle. From Earth, they appear like white bright features waxing and waning over a Mars year. They can reach latitude below 50°. By analogy with the Earth, most observers assumed that the Martian polar caps were composed of water frost, until the first space probes to Mars. Following the Mariner 4 mission, [39] used a simple thermal model to reveal the processes which control the Martian seasonal polar caps: during the fall and winter seasons at high latitudes, the local surface and atmospheric temperatures become cold enough (140 to 150 K depending of the altitude) to reach the frost point of CO_2. CO_2 condenses and forms carbonic ice deposits on the surface which can reach several tens of centimetres thick.

Although it is thought that most of the carbonic ice directly condenses on the surface, a fraction of it also condense in the atmosphere, forming clouds and snowfall that have been detected by the Mars Global Surveyor laser altimeter MOLA [55, 71] and indirectly through their infrared radiative properties [22, 70].

During the spring and summer seasons in a given hemisphere, the seasonal CO_2 cap sublimates back into the atmosphere and the polar caps progressively retreat to the poles.

In the northern hemisphere, the CO_2 cover completely disappears by the beginning of summer, exposing an underlying water ice cap (see below). In the southern hemisphere, the cap recession is asymmetric and strongly varies with longitude [33, 35]. Furthermore, a small residual cap made of "perennial" carbonic ice survives each year through the summer. Why such a difference between the two hemisphere in spite of the fact that both poles receive the same amount of annual insolation? One can show that it is theoretically unlikely that both poles can keep a permanent CO_2 ice cap because one cap will be favored at the expense of the other. Currently, the southern polar cap is favored because of its averaged albedo is higher than it northern counterpart [54]. By reflecting a larger amount of solar radiation, it absorbs less energy and sublimes significantly less. The difference in albedo, however, remains poorly explained. The "CO_2 cycle" causes the global atmospheric mass to vary by more than 30% throughout the year. Surface pressure measurement made from the two Viking probes which landed in the northern hemisphere of the planet in 1976 clearly showed these enormous seasonal variations (Figure 1).

2.3 The dust cycle

The spacecraft mission of the 1970s has revealed that on Mars a significant amount of airborne mineral dust is always present in the atmosphere, from the surface up to altitude of 40 km on average, and sometime 70 km. These dust particles explain the orange color of the Martian sky as observed by the surface probes. They are about one micrometer in size and can be transported by the Martian atmosphere in spite of its tenuity. Dust can be lifted by two distinct meteorological phenomena: dust devils (convective vortices that can reach several kilometers in height and a few hundreds meters in diameter; cf. [10, 19, 68], and more importantly by various kinds of dust storms. Years of monitoring by Mars Global Surveyor show that small dust storms occur every day on Mars [10]. Most of these events take place at the edge of the seasonal polar caps (because the thermal contrast between the carbonic ice and the bare ground induce strong thermal winds) or within the "baroclinic" fronts related to the low pressure zones that sweep the mid and high latitude. Each year, a few tens of these storms last several days and reach "regional" scale with size of several thousands of kilometers. This mostly occurs during southern spring and summer when Mars is closer to the sun on its eccentric orbit.

In some years, but not every year, one or several regional storm can expand to global scale and shroud the entire planet for several months. This happened in 1956, 1971, 1973, 1977, 2001

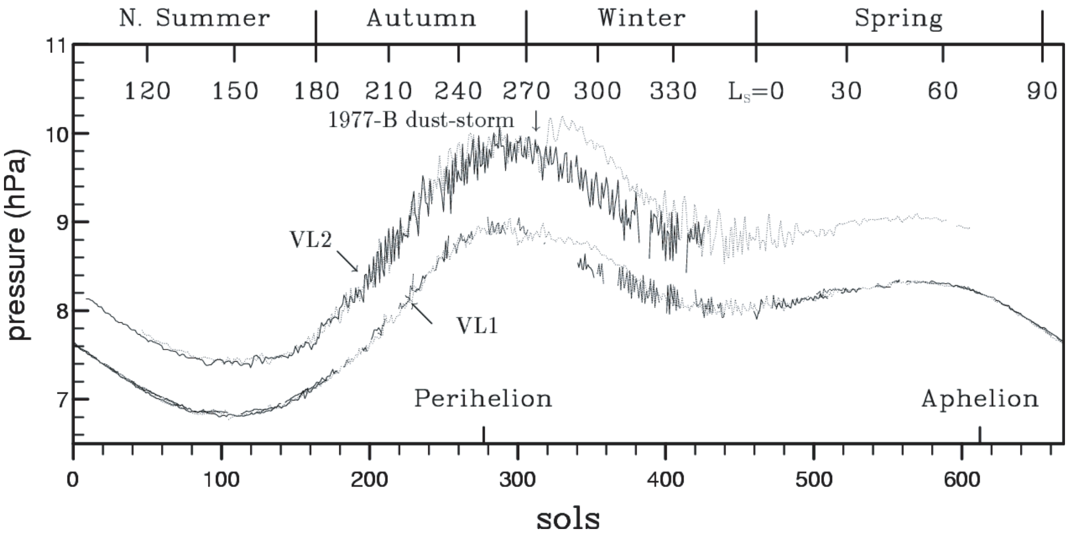

Fig. 1. Time evolution of the surface pressure recorded by the two Viking landers during the first three Martian years of the Viking mission in 1977–1982: Martian year 1 (dotted), 2 (solid) and 3 (dashed) are superimposed on the same graph. The large seasonal variation of the surface pressure are primarily due to the condensation of the atmospheric CO_2 in the seasonal polar caps. The oscillations of pressure observed in fall and winter (with a periods of a few days) are the signature of baroclinic waves, as on Earth. Figure from Hourdin et al. (1993).

and 2007. The 2001 spring global dust storm was especially well observed by the Mars Global Surveyor spacecraft ([9,64] see figure 2).

What is the impact of dust on surface climate? During daytime, by absorbing the solar radiation, the dust reduces the ground insolation and tends to cool the surface. At night-time, dust infrared emission help keep the surface warm, so that the main effect of atmospheric dust is to reduce the amplitude of the diurnal temperature variations, without strongly affecting the surface temperatures on average. However, airborne dust has a major impact on the atmospheric temperature. At sunlit latitude, even when the air is relatively clear, the atmosphere at 20 km is about 30 K warmer than if the atmosphere was completely dust-free. During dust storms, this heating can reach 80 K! Such a sensitivity has no counterpart on Earth. The presence of dust enhances the horizontal temperature gradients on the planet, and thus the atmospheric circulation. Models show that dust injected in the southern tropical atmosphere (where many regional dust storms are observed in summer) enhance the Hadley circulation and reinforce the winds in the tropics. These winds tend to lift more dust, dust reinforce the winds, etc... The development of global dust storms is thought to originate from such a positive feedback mechanism. However, explaining why global dust storms do not occurs every year remains difficult [4,53].

2.4 The water cycle

2.4.1 Water on Mars today

Is there water on Mars? Ladies and Gentleman, please be informed that water is almost everywhere on Mars... in solid or gaseous state.

1. First, relatively pure, white ice is directly exposed at the surface of Mars in an area of about 1000 km in diameter around the north pole. The thickness of this ice layer may vary from a few millimeters at its boundary up to a few meters or a few ten of meters in some locations near its center [34,69].

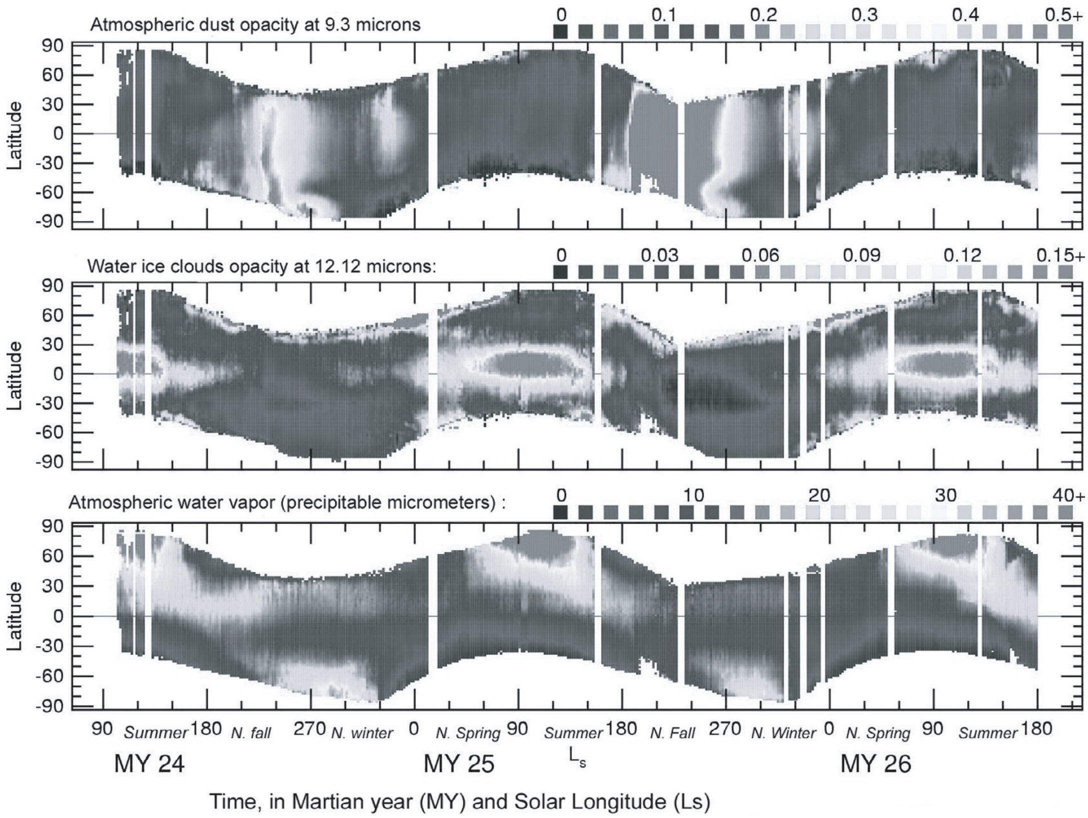

Fig. 2. The climate of planet Mars between 1999 and 2003, as observed by the Thermal Emission Spectrometer aboard Mars Global Surveyor (analyzed by [63]). The color plates represent the zonally-averaged column abundance of dust, water ice and water vapor (observed in early afternoon) as a function of latitude and seasonal time. Seasons are expressed in terms of “Ls”, the aerocentric longitude of the sun (Ls $= 0^\circ$ at northern spring equinox, 90° at summer solstice, 180° at autumn equinox and 270° at winter solstice). Martian years are dated according to the calendar proposed by Todd Clancy (Clancy et al. 2000) which starts on april, 11, 1955 (Ls $= 0^\circ$), now adopted by most Mars climate experts. In each hemisphere the retrieval could not be performed during the coldest seasons at high latitude (fall, winter, spring). The top figure shows the **dust cycle.** A period of relatively clear atmosphere clearest seasons is observed between Ls $= 0^\circ$ and Ls $= 160^\circ$, whereas the period from Ls $= 160^\circ$ to Ls $= 360^\circ$ is more dust laden. This last period is usually characterized by a few regional dust storms (which appear in red during Martian year 24). Martian Year 25 was unusual, whit a quasi-global dust storm that lasted several month staring at Ls $= 180^\circ$ (end of june 2001). The bottom figure shows the **water vapor cycle**. The water vapor column abundance is given in units of precipitable micrometers (pr$-\mu$m). The water cycle is characterized by a maximum of water vapor above the subliming northern polar cap around Ls $= 90^\circ$ (northern summer), which moves southward towards the equator in northern autumn. During southern spring and summer, the water trapped in the seasonal CO_2 ice cap is progressively released when the ground warms after the sublimation of the CO_2. Ultimately, this creates another maximum around the south pole in early summer. The figure in the middle shows the **seasonal cycle of water ice clouds** (described by the clouds infrared opacities). On the one hand, clouds are observed at the boundaries of the polar night in both hemisphere. There, relatively warm air masses transported from lower latitudes are cooled, and water condenses. On the other hand, during the period when the atmosphere is relatively clear (northern spring and summer) and thus cold in altitude, the ascending branch of the Hadley cell transport water vapour in the vertical and creates a cloud belt between the equator and $30\,^\circ$N. These clouds almost completely disappear during southern spring and summer, because the dust laden, perihelion atmosphere is too warm for significant amount of water to condense.

2. This layer appears to cover a much bigger structure made of thousand of layers of ice and dust that have accumulated over more than 3000 meters in thickness (see [14]). These deposits are thought to be comparatively young, preserving a record of the seasonal and climatic cycling of atmospheric CO_2, H_2O, and dust over the past million years [37,41]. Recently, The MARSIS and SHARAD sounding radar aboard Mars Express and Mars Reconnaissance Orbiter have revealed detailed internal structure in the polar layered deposits, and discovered that the underlying rock surface is at a depth of more than 2000 metres below relatively pure ice [57].
3. Observations of the south polar region with Radar also demonstrated that the thick deposits (about 1000 km in diameter, and 2 km thick) accumulated around the pole are also composed of relatively pure water ice [58], currently isolated from the atmosphere by a layer of dry sediments in most location.
4. Near the South Pole, however, the small (300 km), white, bright residual cap is primarily composed of carbon dioxide ice, and for a long time it had been assumed that no water ice layer was present at the surface in the south polar region. However observations of the imaging spectrometer Omega aboard Mars Express has revealed the presence of perennial water ice deposits at the edges of the CO_2 ice bright cap; and even in large areas tens of kilometers away from it. Most likely, the permanent CO_2 ice cap lies on a extended water ice layer [5].
5. In both the northern and southern hemisphere, poleward of about 55°–60° latitude, the Mars Odyssey Gamma-Ray Spectrometer investigation has shown that where ice is not exposed at the surface, it is still present just beneath the surface (below an ice-free layer a few centimeters thick), typically in the form of a dirty ice layer more than one meter thick and with no less than 50% of ice. What had actually been measured was the presence of large amount of hydrogen, which can be detected through an emission of gamma ray and the capacity of hydrogen to reduce the neutron flux emitted by the surface. No other components than water ice seemed likely to explain such a high amount [18]. Moreover, in these areas the unique morphology of the ground is consistent with the presence of a few meters thick ice layer coating the surface (see a synthesis in [28]). In 2008, the NASA Phoenix mission landed near 69 °N in order to confirm the presence of ice and better understand its origin and its environment. As expected, a layer of ice was found just a few centimeters below the surface (Figure 3).
6. Below this dirty ice layer, and even at lower Martian latitudes, it is likely that the large pore volume of the Martian subsurface regolith might be partly filled by ice. Calculations of the thermodynamic stability of ground ice suggest that it can exist very close to the surface at high latitudes, but can persist only at substantial depth (several hundred meters) near the equator [66]. An observational evidence of the subsurface ice might be the presence of impact craters with distinctive lobate ejecta that are not found on the moon, and that apparently owe their morphology to the melting and vaporizing of ground ice during the impact. The size frequency distribution of these craters is consistent with the depth distribution of ice inferred from stability calculations.

2.4.2 The seasonal atmospheric water cycle

The cycle begins on the northern permanent polar cap, where ice is exposed at the surface. In summer, the ice is warmed by the sun and sublime. For a few months, the north polar region becomes a source of water vapor which is transported away within the atmosphere. During the rest of the year, most of this water ultimately comes back to the northen polar cap through various transport mechanism [51,60]. The cycle is closed and near equilibrium.

The amount of water involved in the seasonal water cycle is small. If one could precipitate the water content of the atmosphere on the surface, a layer thinner than a few tens of micrometers would be obtained even in the "wettest" regions (Figure 2). In the cold martian conditions, though, saturation is often reached. Therefore, clouds form in the atmosphere and frost can condense onto the surface. The atmospheric water vapour should also be able to diffuse into the porous subsurface. All these processes make the martian water cycle. Is this cycle closed? today

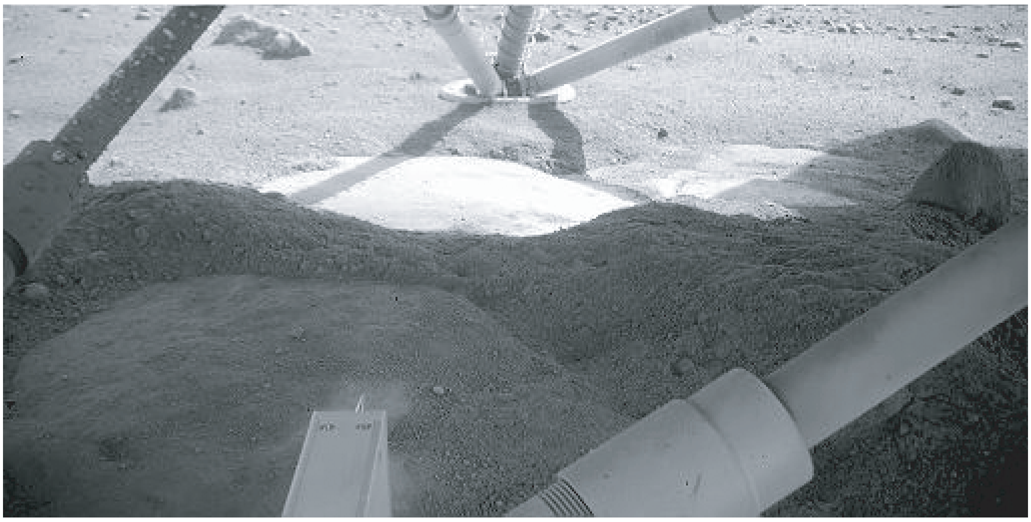

Fig. 3. An image of the Martian surface beneath NASA's Phoenix Mars Lander taken by Phoenix's Robotic Arm Camera (RAC) on the eighth Martian day of the mission on June 2, 2008. A superficial dust layer, shown in the dark foreground, has been blown off by Phoenix's thruster engines, exhibiting an ice rich layer a few centimeters below the surface. The presence of the ice in Mars high latitudes had been remotely detected by the Mars Odyssey Gamma-Ray Spectrometer investigation in 2002.

there is one location on Mars where water condense without ever being able to sublime: the residual south polar cap. The permanent residual CO_2 frost is so cold (142 K) that water can only exist in solid state. It certainly serves as cold trap for water. On average, water vapor is thus transported from the north pole to the south pole. Could that have always been the case? It is most likely that things where different 10^3 to 10^5 years ago (see below), and in particular that the cycle may have reversed in the past [52].

2.4.3 Liquid water on Mars today

To form liquid water – and possibly create an environment suitable for life as we know it – one not only need water, but also temperature above the freezing point (0 °C for pure water), and pressure above 6.1 mbar. Such conditions are not uncommon on Mars, for instance in the lower plains in summer in early afternoon. They last only a few hours at most, however, and only the first few millimeters below the surface can be heated above 0 °C. Because of the low vapor pressure of water in the atmosphere, any ice that may be present at the surface (in the morning, for instance) sublimates into the atmosphere well before it can melt (e.g. [21]). The existence of liquid water in a "metastable" state in some specific circumstances has been suggested [29], but remains unlikely.

In such an environment, where could liquid water be find? More likely at several thousands meters below the surface, where water present in the ground pores could be heated by the geothermal flux [66]. The most "optimistic" scientists imagine that liquid water aquifer could exist at much shallower depth up to a few tens of meters below the surface thanks to local geothermal activities, but, here again, this remains speculative.

3 A few millions years ago: The recent Martian paleoclimates

3.1 Climate changes due to orbital parameters variations

The climate that we observe on Mars at the present time is probably not the one that the planet enjoyed as recently as a few thousand years ago. There are clear signs that the planet is in constant evolution on such timescales. Why? As on Earth, the climate on Mars depends on the planet orbital and rotation parameters, and in particular its obliquity (inclination of Mars axis of rotation on its orbit plane). In the Earth case, such oscillations are small ($\pm 1, 3°$ for the obliquity), but they are thought to have played a key role in the glacial and interglacial climate cycles. In the Mars case, calculations performed by J. Laskar's team [36,38] have shown that Mars obliquity did vary widely and somewhat erratically in the past, between 0° and more than 60° (the current obliquity is 25.2°). Needless to say that these variations must have had a strong impact on Mars climate. A quantified description of these past climates is not easy because one have to predict the response of a complex system that include the atmospheric circulation and the coupled CO_2, dust, and water cycle. Nevertheless, on the basis of theoretical considerations and with the help of numerical climate simulations, we can speculate about the major changes.

3.1.1 During periods of low obliquity

With an obliquity below 20°, the seasonal cycle is weaker than today. The latitudinal extension of the seasonal polar caps is reduced. However, the polar regions experience a net decrease in solar heating (the sun is lower on the horizon) and thus a net cooling. It is likely that the mass of frozen atmosphere trapped at the pole (currently near the south pole) increases at the expense of the total atmosphere mass. Models also show that in such conditions the water and dust cycle are much less active. The atmosphere is thinner and clearer. Mars is then a frozen world.

3.1.2 During periods of high obliquity

Beyond 30° of obliquity, the seasonal cycle is stronger than today. For instance the CO_2 ice seasonal polar caps extend to the tropics in winter when the obliquity reaches 40°. In the polar regions, the increase of annual mean insolation leads to a warming of the relatively deep subsurface. The CO_2 trapped in solid state in the perennial polar caps or in absorbed form in the regolith, is released until these CO_2 reservoirs are depleted [32]. How much CO_2 can join the atmosphere-seasonal cap system is unknown, but one can imagine a martian atmosphere thicker than today, with a more intense circulation forced by the strong seasonal cycle [27]. This atmosphere should be able to lift and maintain large amount of dust airborne. In summer, the polar water ice reservoir is strongly heated and releases tens to hundred times more water than today, inducing a very active hydrological cycle (vapour, clouds, frost). Beyond obliquity of 35° to 45°, computer simulations of the Martian climate suggest that warming of any ice left at the poles would liberate such a large amount of water into the atmosphere that, in certain areas, water vapour would condense and precipitate out much more readily than it could sublime. In these areas, ice would therefore have accumulated (as long as there was still a source at the pole) and might even have formed glaciers [23,40,50]. The remains of these glaciers (moraines) and possibly rock covered glaciers (Figure 4) have indeed been found where the models indicate they once existed, on the flanks of the great volcanoes of Tharsis [23], to the east of the Hellas Basin, or in the Northern Hemisphere mid-latitudes (Madeleine et al., submitted, 2008). Climate models also suggest that, depending on the oscillations of the obliquity, water could accumulate and cover the high latitudes (>60°) in each hemisphere with an ice layer a few meters thick. It is likely that part of this ice is still present there today, buried below dry sediments that prevent further sublimation [40]. This would explain the Mars Odyssey and Phoenix observations (Figure 3) mentioned above and the surface morphology.

Today, it seems that a large amount of the ice that may have been transported in and out the polar regions is back at the pole. If this scenario is confirmed, the presence of thick deposits composed of hundreds of alternatively dark and bright layers in the polar regions can probably be attributed to the past oscillations of the climate [35,41].

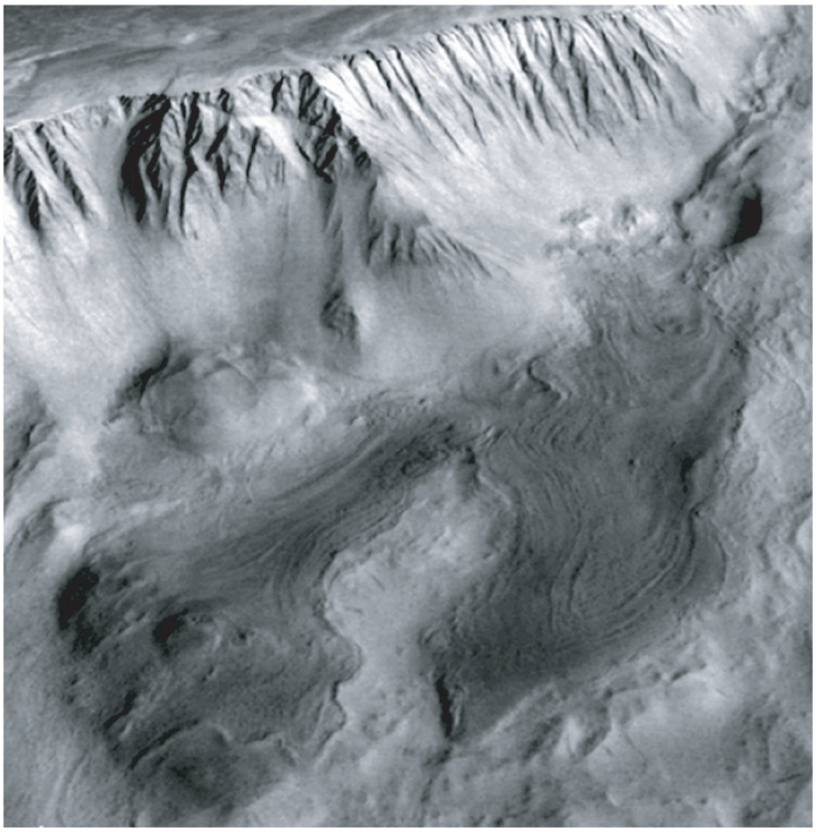

Fig. 4. Remnant of glaciers discovered in the tropical zones of Mars near the scarpfoot of the great volcano Olympus Mons by the Mars Express' HRSC camera. This small "rocky glacier" composed of ice covered with rocks and sediments is surrounded by large deposits characteristic of past glacial activities covering an area hundreds of kilometer across. How could such glaciers have formed on a planet where surface ice is unstable except at the poles? Computer simulations of the Martian climate at times of high obliquity show that the air was then much richer in water vapour than it is today. Impelled by westerly winds onto the flanks of the volcanoes, this moist air was abruptly cooled. Ice condensed out and fell to the surface. It is estimated that the rate of accumulation was something like a few centimetres per year, enough to form a glacier over thousands of years [23]. Now, most of the water has evaporated; but, at the heart of the rocky glacier, a small amount of ice mustmay remain beneath its protective layer of rocks and dust.

4 More than 3 billions years ago: The youth of Mars

4.1 Evidences for sustained liquid water on Early Mars

About half of the surface of Mars is extremely ancient, dating back from prior to 3.8 billions years ago, a time when the impact rate from infalling meteorites and planetesimals was much higher than today. We can estimate the age of the surface because they are densely cratered from the heavy bombardment period. This part of the Martian surface, mostly in the southern highlands, has also kept the record of a period where the environment was much different from what it became after. There is evidence that at this time, liquid water was present on the surface of Mars and could have formed rivers, lakes, and possibly an ocean. These are discussed below:

- *Valley networks.* Valleys, with characteristics very similar to terrestrial river drainage valleys, were discovered in the seventies by the Mariner 9 orbiter. Smaller channels coalesce downhill into larger valleys, to often take the form of a dendritic network. These valleys are observed on most of the surfaces older than 3.5–3.8 billion years, but almost none has been identified on more recent terrain. This suggests that Mars enjoyed an environment suitable for the formation of these valleys more than 3 billion years ago (at least periodically), but that such conditions never repeated later. Was the climate different? While there is still substantial debate as to whether these channels were carved by water that drained from the surface following precipitation from the atmosphere or were formed by the release of water from within the crust in a process known as "sapping" (cf. [8,65]), It is widely accepted that liquid water was involved and that it would have taken substantial periods of time to form them. This suggests that the climate must have been at least suitable for stable surface liquid water at the time. Did it rain on Mars? That is the debated issue. However, the recent exploration era is revealing more and more valley morphologies that suggest that precipitation and runoff was involved [1,16,46].

- *Lacustrine deposits*?: If Mars enjoyed a climate that allowed large amount of liquid water to flow on its surface, it seems logical that some of this water could have accumulated in some location to form lakes, or even an ocean. This scenario remained quite speculative until the Mars Global Surveyor camera discovered new evidences of deposits within craters that have an appearance similar to layered lacustrine deposits, deltas, sedimentary terraces and shorelines [43]. These deposits are thought to have been buried for long periods and were exhumed only recently (there are few impact craters superposed on the deposits, but the stratigraphic relationships suggest an old age). Well-defined layering have been identified within these deposits, supporting the idea of standing water, although windblown sediments could explained some of the observations. In some other cases however, the observations are not ambiguous. Figure 5, for instance, shows a delta-like structure that present all the characteristics of alluvional deposits [44].
- *Erosion rate:* A detailed analysis of the ancient terrains reveals that old impact craters larger than about 15 km in diameter have a substantially degraded appearance. Crater rims, ejecta blanckets, and central peaks have, in many cases, been completely removed, and the crater interiors have been filled in with debris. Craters smaller than about 15 km have been erased entirely. However, craters formed in regions a few hundreds of millions years younger are much better preserved. This observation suggests that in the distant past, before 3.8 billions years ago, the erosion rate, was a thousands of time more efficient than later in the history of Mars. While this erosion could have many possible causes, it is thought that liquid water was the eroding agent [17].
- *Mineralogy*: On Earth, the composition of many terrains point to their formation in the presence of liquid water (e.g. hydrated materials). On Mars, such evidence are more seldom. The observations gathered by the thermal infrared spectrometer TES aboard Mars Global Surveyor and by the near infrared imaging spectrometer Omega aboard Mars Express suggest that most surfaces are either of volcanic origin, or covered by dust [6,12]. However, in 1998, TES revealed the presence of three regions with exposed surface enriched in mineral hematite, an iron oxide weathering product inferred to have been precipitated from water flowing through the crust. One of this region, *Sinus Meridiani* was selected to be explored by Opportunity, one of the two Mars Exploration Rover that began its mission in January 2004. Opportunity did confirm the presence of Hematite, and made an even more interesting discovery: it detected the presence of sulphate salts (jarosite: $KFe_3(SO_4)_2(OH)_6$; kieserite: $MgSO_4$, H_2O) in the sedimentary outcrop of the area, with physical characteristics indicative of aqueous transport [67]. On this basis, the Opportunity team concluded that these rocks probably recorded episodic inundation by shallow surface water, evaporation, and desiccation. At the same time, OMEGA actually discovered and mapped hydrated sulfates – kieserite, polyhydrated sulfates and even gypsum ($CaSO_4$-2(H_2O)-mostly in light-toned layered terrains located in Terra Meridiani, Valles Marineris and Margaritifer Sinus [24]. Even more interestingly, The OMEGA team discovered clays (phyllosilicates, primarily iron/magnesium smectites) in several locations restricted to the most ancient terrains, suggesting that clays formation may have taken place primarily during the earliest portion of Martian history [59]. Clays were probably formed by the action of liquid water on volcanic rocks, over tens of thousands of years. Altogether, the

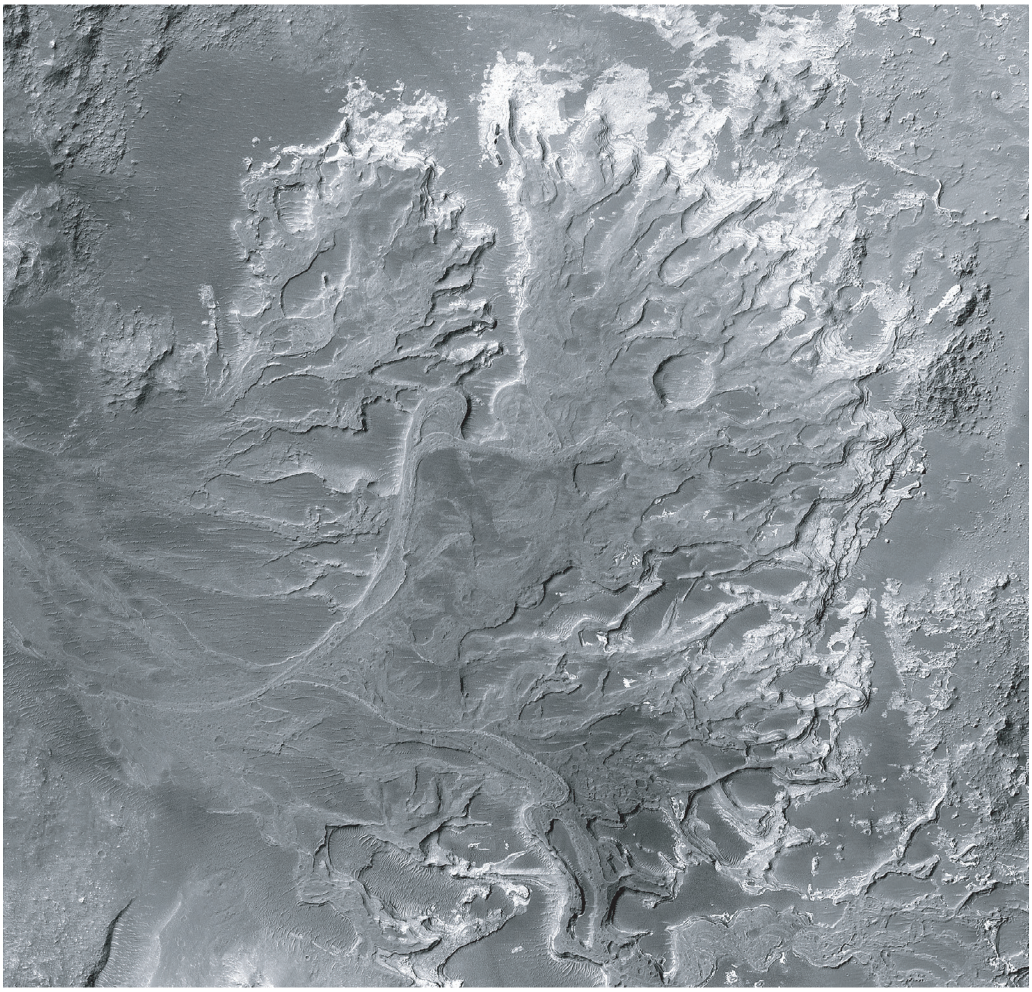

Fig. 5. Remnants of sedimentary alluvial fans analogous to a river delta (MOC camera, Mars Global Surveyor, NASA/JPL/MSSS). These ancient deposits have probably been covered, eroded and exhumed throughout the long Martian geological history. The observation of such a characteristic landform provides a clear, unequivocal evidence that some valleys on Mars experienced the same type of on-going, or, persistent, flow over long periods of time as rivers do on Earth, and that many of the other sedimentary rocks that are observed on Mars (but which do not exhibit such obvious delta-like characteristics) should also have been deposited in a liquid (probably water) environment [44].

mineralogical investigations suggest that Mars experienced, early on, a period when liquid water was probably abundant, and able to soak soils during episodes long enough for clays to form. Later, in a drier and more acidic environment, sulphated salts were more likely to form [7].

4.2 The early Mars climate enigma

The possible existence of relatively warm conditions suitable for surface liquid water on Mars 3.8 billions years ago is unexpected. Most expert believe that at that time, the young sun was less dense than today and its luminosity 25% lower than at present time. Since Mars is about 1.5 times more distant from the sun than the Earth, the solar energy available on Mars then was only one third of what we enjoy on Earth today. The radiative equilibrium temperature of the planet should have been −75 °C, not taking into account the atmosphere. In such conditions, what could have made the climate so warm and wet? For 20 years, this enigma has been a typical subject of collective scientific progress, with each new theory dismissing the previous one. The "easiest" way to warm early Mars is through the greenhouse effect of its atmosphere. The composition of the early Mars atmosphere is difficult to know for sure, but it was probably mostly composed of carbon dioxide with a surface pressure between a few hundreds of millibars to a few bars. Such amounts are consistent with the initial volatile inventory of a planet like Mars, and it is likely that large amount of CO_2 and H_2O should have been released in the atmosphere by the substantial volcanism that occurred on early Mars, associated with the formation of the volcanic plains and the Tharsis bulge [56]. Both CO_2 and H_2O are greenhouse gas, but their ability to warm the planet through greenhouse effect is limited, and they may not have been able to solve the early Mars climate enigma by themselves (See review in [25]). Other greenhouse gas, such as NH_3, CH_4 or SO_2 have been proposed to help solve the enigma, but they should have been photochemically unstable in the early Mars atmosphere and rapidly exhausted, unless produced by a surface or subsurface source (volcanism? life?). However, the presence of Sulfate salts on Mars have motivated recent studies involving SO_2 in the atmosphere [31]. Another possibilities is that Mars was warmed by carbonic ice clouds [21]. These clouds tend to form in a thick CO_2 atmosphere. Models show that they can reflect a significant part of the thermal infrared radiation emitted by the surface and warm the planet through an exotic "scattering greenhouse effect".

It is not clear how much greenhouse warming is required to explain the available geological evidences. Some of them could be explained by the large geothermal heat flux (5 to 10 times the present-time values on average) that contributed to warm the near sub-surface and probably induced an intense geothermalism [65]. One can also imagine that the large impacts that often occurred at the end of the heavy bombardment could have played a role episodically. For instance, impacts produced global blankets of very hot ejecta that could have warmed the surface, keeping it above the freezing point of water for periods ranging from decades to millennia [61].

5 Conclusion

The new era of exploration of Mars that was initiated by NASA in 1997 and followed by ESA in 2003, is revolutionizing our understanding of the present and past of planet Mars. Year after year, Mars climate sciences are making progress. We can know study the present meteorology with observing and modeling tools which are analogous to Earth studies by many aspects. This allows scientists to truly perform comparative planetology, in which tools and concepts that have been developed for the Earth can be tested and enriched by studying other planetary atmosphere.

With regard to Mars past climates, more and more data are also available. However, many of these observations appear to be contradictory. In such condition, there is no consensus on what really happened on Mars, on what has been the climatic evolution, We know that there have been multiple kind of climate on Mars, because the planet environment strongly varied with the oscillations of the planet orbital and rotation parameters as well as with the evolution of the content of its atmosphere. For many scientists, the key issue remains the existence of liquid water and the possibility of life. I personally would conclude that, although Mars appears to have enjoyed conditions suitable for sustained liquid water on its surface 3.7–4.2 billion years ago, it seems that afterward the martian climates did not allow surface liquid water except during very episodical events. For several billions years, Mars has probably not been very suitable for life as we know it, except maybe in the deep subsurface. However, one can expect that new discoveries will soon, confirm or disprove this opinion, bring new insight to the problems, and probably question some of the "certain facts" presented in this chapter…

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