THE EVOLUTION OF THE PAST ATMOSPHERE OF MARS.

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Abstract.

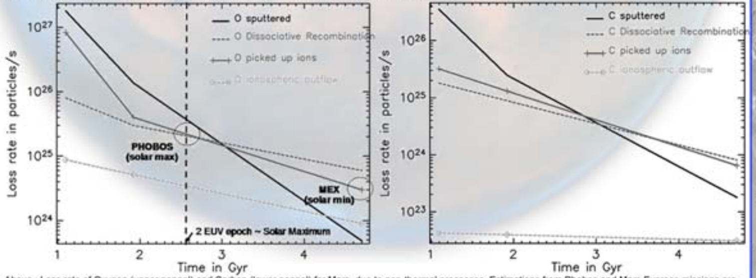
Past evolution of terrestrial planets is difficult to study due to the lack of data and in situ measurements. However, it is necessary in order to explain some of the features that are observed by recent missions.
This work is meant to show that even with the few data we have and by using simple straightforward models, it is possible to have some answers about the evolution of Mars during the last 3 Gy. We study possible states of the past Martian atmosphere consistent with present observation through a simple evolution model based on realistic outgassing scenarios and atmospheric loss. We focus on CO_2 as the most likely main gas present in the atmosphere at that time and involved in large scale and long term processes.
Volcanic degassing is obtained through the use of results from numerical model analysis that yielded the evolutions of crust production rates (Breuer et al., 2003 and 2006, Manga et al., 2006). By evaluating the contents of the lavas, the amount of volatiles that are released can be estimated through different scenarios.
The mechanisms leading to the loss of the Martian atmosphere are all thought to be part of the atmospheric escape rather than some surface reservoirs such as carbonate formation as no carbonate has been found on Mars to this day. Atmospheric escape is due to non thermal processes (involving solar emissions) as opposed to thermal processes (such as hydrodynamic escape). We used measurements from ASPERA and Mars Express and models from Chassefière et al. (2006) to estimate the amount of lost atmosphere.
Thus we obtain evolutions of the CO_2 pressure that are consistent with the present state of the atmosphere. It first appears that a present-day crustal production of at least 0.01 to 0.1 km^3/year is needed for the atmosphere to be at steady state.
Moreover our models provide us with a rough constraint on the CO_2 contents of the Martian mantle. It seems it should be lower than 200ppm in order to fit with present-day conditions. Higher concentrations would lead to thicker atmospheres due to intense release of gases by late volcanism.
We also witness around 3 Gy ago a rapid loss of the primary (and primordial) atmosphere due to atmospheric escape. It is finally found that for most of the scenarios (we investigate a wide range of mantle compositions and atmospheric escape models) the present atmosphere is of volcanic origin and has been created between 1 Gy and 1.5 Gy ago. If the volcanic activity and the degassing are intense enough then the atmosphere can even be entirely secondary and as young as 500 My, meaning that the present Martian atmosphere can be very young.

A simple model is used to compute the evolution of different volatiles over time in the atmosphere of Mars during the last 3 Gy. We focus on Water and CO_2. On the first order we consider degassing (input of gases) and escape (which removes the gases from the atmosphere) as the two main processes which control the history of the atmosphere.

Atmospheric Escape.

Since our model focuses on the last 3 Gy, the main processes for atmospheric escape are non-thermal. We use data from Chassefière, Leblanc and Langlais (2006) for sputtering, dissociative recombination, ionospheric outflow and ion pick-up to estimate the amount of CO_2 and H_2O lost to space.
-Sputtering: ions produced in the corona or in the ionosphere reimpact the neutral atmosphere and lead to the ejection of neutral particles.
-Dissociative recombination: ions from the ionosphere recombine with electrons and form energetic neutrals with enough energy to escape.
-Ion pick-up: ions produced in the exosphere are dragged along by the solar magnetic field lines wrapping the planet.
-Ionospheric outflow: ions are produced within the ionosphere and can flow up to the ionopause where they are dragged by the solar wind.

The change of slope in the same figure is attributed to the non-linearity of the processes. We suppose that one oxygen atom escapes with two hydrogen atoms and that one carbon atom is associated with two oxygen atoms. This enables us to have an estimate of the amount of CO_2 and H_2O lost to space. The H_2O loss rate is at least one order of magnitude higher than CO_2 loss rate. So here, we use CO_2 loss rate as the limiting parameter.As new data becomes available thanks to missions, we adapt our models. Latest ASPERA measurements for the present-day atmospheric escape might give insight in the evolution of the atmosphere and so have been included (Carlssona et al., 2006). The values are somewhat lower than what was found previously (and is used Chassefière et al., 2006) since Carlssona et al. give 0.29kg/s for the CO_2 loss rate, which probably corresponds to the solar minimum. Our other sources (mainly the results from modelling as presented by Chassefière et al., 2006) tend to suggest values around 2 to 5 times higher.Since our model focuses on the last 3 Gy, we can neglect the effect of heavy bombardment, which is thought to have efficiently removed up to 99% of the Martian atmosphere and which occurred early in the history of the planet (before 3.9Gy, the approximate age of the end of the late heavy bombardment).



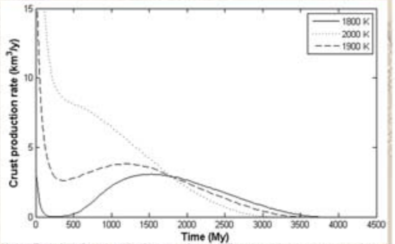
Above : Loss rate of Oxygen (upper pannel) and Carbon (lower pannel) for Mars, due to non-thermal processes. Estimations from Phobos and Mars Express missions are also shown (reproduced Chassefière et al. 2006).

Degassing.

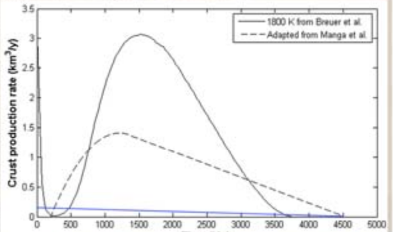
Volcanism is the major input of CO_2 that can be found for the atmosphere of Mars, considering the absence of any other major reservoir such as carbonates or CO_2-rich polar ice caps. Geophysical modelling of the activity of Mars provides us with estimations of the amount of lavas produced that will allow us to deduce the amount of volatiles that are released into the atmosphere.
As an input for the amount of volatiles released into the atmosphere, we mainly use data from numerical studies from Breuer and Spohn, (2006) and Manga et al. (2006) but also consider other sources such as O'Neill et al. (2007). Breuer et al. employed a parameterized model of stagnant lid convection with crust production, core cooling and mantle melting. The model is constrained by both crustal thickness and magnetic field history, applying data from Mars Pathfinder, Mars Global Surveyor and Mars Express.

We compared these results with other data from Hartmann and Neukum (2001), obtained by observation of the surface of the planet. Observations seem to show that activity is not as strong as the numerical seems to imply. On the other hand, these observations are not taking into account intrusive processes that may occur. The estimates from O'Neill et al. (2007) are even lower than those from Manga et al. and fit better with the observation of the surface of Mars. They propose volcanic rates ranging from over 0.17 km^3/yr for the Hesperian to around 10^{-4} km^3/yr at present.

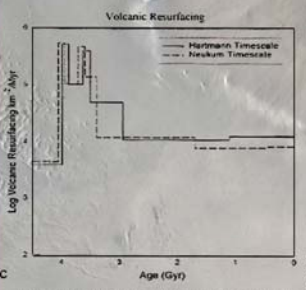
Few well constrained and dependable data exist about CO_2 content; instead, information given by the study of Martian meteorites is often used.
We show some data we used in this study. Several results on Martian meteorites lead to the assumption that CO_2 is quite rare in the Martian mantle, but data exist that would imply rather larger CO_2 contents. If Mars is not much different from the Earth, its mantle might contain a lot more CO_2 than Martian meteorites seem to suggest. Another hypothesis (Kuramoto, 1997) even hints at larger CO_2 concentrations due to higher silicon content in the core. It has however been suggested that concentrations much higher than 1000 ppm would not be consistent with today's data.
However, all samples used above to estimate CO_2 contents are degassed samples, depleted with regard to their initial state. One important parameter is not known and can not be constrained: it is not known how efficient the degassing is on Mars.



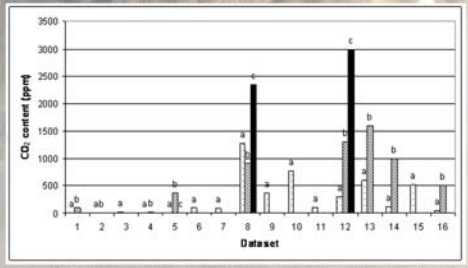
Above: Evolution of crust production rates, for two different mantle temperatures, adapted from the results of a numerical model for Martian inner dynamics from Breuer et al. (2006). The solid line corresponds to the main model considered here, with a 1800K mantle. The dashed line corresponds to a slightly hotter 1900K mantle and the dotted line to a 2000K mantle.



Above: Evolution of crust production rates, for two different numerical models. The solid line corresponds to the cool mantle case in figure 1, adapted from Breuer et al. 2006. The dashed line is adapted from a numerical model by Manga et al. (2006). The blue line shows an estimation of aproximate values found by O'Neill et al. (2007).



Above : Evolution of volcanic resurfacing over time. Note that we are only interested in the last 3 Gy here and that the scale shows a surface per Myr which tends to complicate evaluations of melt volume. (Reproduced from Hartmann and Neukum (2001).



Above: Compilation of estimates from the literature of CO_2 composition of the degassed lavas on Mars. Each data set is composed of one, two or three values, being either different results or extreme values as indicated below. 1. M.M. Grady et al. 2004, Martian meteorites. 2. ALHA77005, a) Gooding (1990), b) Wright (1986). 3. EETA79001A, Wright (1986). 4. EETA79001B, a) Gooding (1990), b) Wright (1986). 5. EETA79001C, a) Gooding (1990), b) Gooding (1990), c) Wright (1986). 6. Shergotty, Wright (1986). 7. Chassigny, Wright (1990). 8. EETA79001A Gooding (1990). 9. EETA79001C, Gooding (1990). 10. Nakhla, Gooding (1990). 11. Nakhla, Carr (1985). 12. Terrestrial MORBs, Jambon (1994), a) Minimum value, b) mean value, c) maximum value. 13. Terrestrial mean abundance, Jambon, a) Minimum value, b) Maximum value. 14) CO_2 content of Martian lavas used in this study, a) minimum value, b) maximum value. 15) Estimate for Iceland volcanism (Gslason et al., 2002) used in O'Neill et al., 2007. 16) Earth upper mantle content by Trull et al., 1993.

Evolution of the Martian Atmosphere: Results.

First results are shown to the right on the upper panel. We wanted to have an estimation of the state of the atmosphere at any given time with the main constraint that we obtain the real situation at the present time. For CO_2 that means we enforce present pressure to be just below 10mbars. We did not go back further than 3 Gy due to earlier events such as bombardment, and hydrodynamic escape.

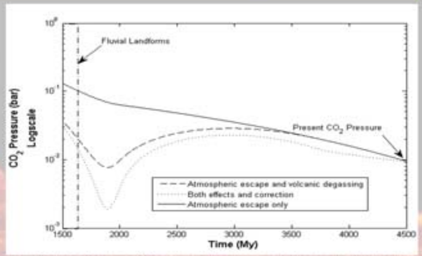
Here we can first see CO_2 maximum pressure when only atmospheric escape is considered. This means that even 3 Gy ago it was unlikely for Mars to have a thick CO_2 atmosphere.
The two other curves take into account degassing based on crustal production rates from Breuer et al. (2006). Values for the maximum CO_2 pressure are significantly lower and stay in the order of several to several tens of millibars. What is really interesting is the minimum around 2Gy. It shows we can obtain today's atmosphere for Mars without needing much primordial atmosphere. In fact most of what we see nowadays might well be a produce of volcanic activity (thus a secondary (and quite recent) atmosphere) instead of the remnant of a primordial atmosphere.

Before the significant drop in pressure occurring 2.5 Gyr ago, the CO_2 pressure was at its highest for the period of time we study here. This relatively dense atmosphere happens to coincide with the occurrence of fluvial landforms as proposed by Mangold et al. (2004). Since the pressure is not that much higher than the one we observe during the late period of activity (around 1.5 Gy ago), it might be possible that liquid water existed at this time on the surface.
Assuming the proportions between CO_2 and H_2O are roughly the same in Martian lavas as in those from Earth (Philips et al., 2001, use 0.65 wt % CO_2 and 2 wt % H_2O on Earth for Hawaiian basaltic lavas), and that the only source of water and CO_2 is volcanism, we can calculate an approximate H_2O partial pressure.

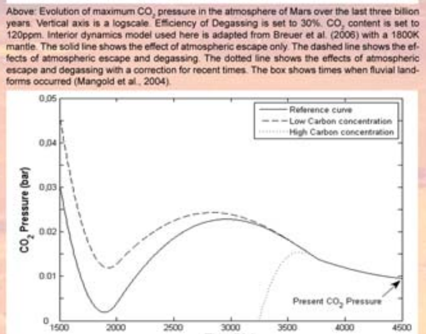
$$P(H_2O) = P(CO_2) \times n(H_2O) / n(CO_2)$$

where P(i) is the partial pressure of component I and n(i) is its molar fraction.
We find that the partial pressure for H_2O would roughly amount to some 150 mbar around 1.5 Gy ago. This is well above the triple point in a water phase diagram and thus, provided the surface temperature is high enough, liquid water could have been present at least during brief episodes, such as volcanic ones that would release large quantities of SO_2 in the atmosphere, thus leading to short term warming.

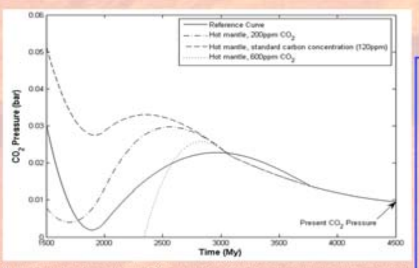
We considered several models to test the influence of CO_2 content in the melted material used for the degassing. We observe that for very low CO_2 degassing, a part of the primordial atmosphere remains. However, as soon as the amount of CO_2 available gets higher, the maximum CO_2 pressure drops. This means that with these models, the whole present atmosphere is secondary and originates only from recent volcanism. We can estimate an age for these atmospheres and it can be as young as 1.5 Gy. Other models where used to study the influence of global activity on the evolution of maximal CO_2 pressure. Breuer et al (2006) give several curves for crust production rates depending on the initial temperature of the mantle. We compared results for a 2000K mantle and a 1800K one. (Figure to the right, lower panel). They tend to show the same kind of behaviour.



Above: Evolution of maximum CO_2 pressure in the atmosphere of Mars over the last three billion years. Vertical axis is a logscale. Efficiency of Degassing is set to 30%. CO_2 content is set to 120ppm. Interior dynamics model used here is adapted from Breuer et al. (2006) with a 1800K mantle. The solid line shows the effect of atmospheric escape only. The dashed line shows the effects of atmospheric escape and degassing. The dotted line shows the effects of atmospheric escape and degassing with a correction for recent times. The box shows times when fluvial landforms occurred (Mangold et al., 2004).



Above: Evolution of maximum CO_2 pressure over time for several CO_2 contents of the lavas. Model is adapted from Breuer et al. (2006) with a cool mantle. Efficiency is set to 30%. The solid line shows the evolution with low CO_2 content (120ppm). The dashed line is for lower CO_2 content (100ppm). The dotted line is for a higher CO_2 content (600ppm).



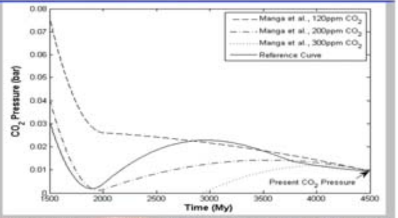
Above: Evolution of the maximum CO_2 pressure for different interior dynamics and crust production models adapted from Breuer et al. (2006). Three CO_2 contents are used. Efficiency is set to 30%. The cool mantle model is included for comparison (solid line). All other models use the hot mantle model. The dashed line shows results for 120ppm CO_2. The dotted line for 600ppm. The dashed and dotted line for 200ppm.

We also used an alternative model for the crust production rate, adapted from a study by Manga et al. (2006) as discussed above.
The upper right hand panel shows a comparison of results obtained with this new model to those based on Breuer and Spohn (2006).
For the low end value of our range of mantle compositions (120 ppm CO2), the evolution of maximum CO_2 pressure does not show any minimum in the early period (around 2.7 Gy). Instead we observe a change in the slope that corresponds to the transition from the 3 EUV to the 1 EUV era. That is the only striking feature apart from the relatively high CO_2 pressures (compared to the other model) 3 Gy ago. The model allows up to 70mbar CO_2 in the atmosphere at that time.

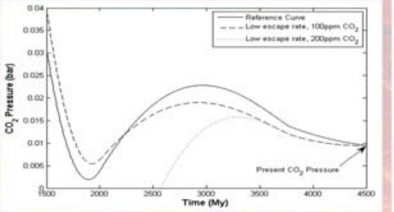
O'Neill et al. (2007) propose a different range of values for the volcanic CO_2 input flux. We ran the model with their values, using both low (≈100 ppm) and high (≈500 ppm, i.e. what O'Neill et al. use in their calculations) CO_2 concentrations and a 100% efficiency.
Results for high CO_2 contents (that correspond to Earth-like conditions) are similar to what we obtained with lower concentration in our previous models and exhibit the same features with the same range of values for the pressure at any given time. However with low volatile contents, the atmospheric escape is dominant.

On the middle right hand panel we compare two different possibilities for atmospheric escape models: one adapted from Chassefière et al. (2006), the other from ASPERA present-day data (Carlssona et al. 2006). The one where new ASPERA measurements are used presents a structure that is similar to other results. The lower present-day escape implies that the planet could have lost less CO_2 to space during the past few tens of million years in this new model than in the other (with higher escape). It thus means that past atmosphere was even less dense with this low escape model. Indeed, in this case, the Martian atmosphere seems to be quite stable for the past two billion years with a pressure staying around present-day values (never exceeding 0.02 bars). Again this atmosphere is a secondary atmosphere. Between 2.5 Gy and 2 Gy ago it would have been building up due to volcanism and prior to this, nearly no atmosphere existed for a while and it can be said that the primary atmosphere had been lost.

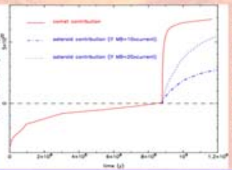
The lower right hand panel shows a possible origin for the higher CO_2 pressures that occur around 3Gy ago in our models. Late heavy bombardment could be intense enough to contribute to the volatile inventory on Mars without blowing off the atmosphere and lead to the several tenths of bar our model shows.
Our future investigations will incorporate this possibility and the next developments of the model will see this input of volatiles added in order to have better estimates of the atmospheric pressure during the older periods.



Above: Evolution of maximum CO_2 pressure; comparison of two models. Three CO2 contents are used here (120, 200 and 300 ppm). Efficiency is set to 30%. The Breuer et al. (2006) model with low (1800K) mantle temperature is used for the solid line (120 ppm CO2). The Manga et al. (2006) model is used for the dashed line (120 ppm), the dashed and dotted line (200 ppm) and the dotted line (300ppm).



Above: Evolution of the maximum CO_2 pressure; Variations of the escape rate. Efficiency is set to 30%, degassing model is taken from Breuer et al.. The reference curve uses estimations from Chassefière et al. 2006 and a 120ppm CO_2 concentration (solid line). Estimations from Carlsona et al. for the (slightly lower) escape rate are used for the dotted (200ppm) and the dashed (100ppm) lines.



Left side: Estimate of the contributions of comet and asteroids to the mass inventory during the late heavy bombardment and thus to the volatile inventory (from Morbidelli).
Note that 7.10^{22}g of incoming material with a water contents of 2% correspond roughly to 0,35 Bar water (equivalent pressure) 3,1 Gy ago.

Conclusions and perspectives.

Our results suggest that the present-day atmosphere seems to be a secondary atmosphere almost entirely or entirely created by volcanic degassing, with low CO_2 contents in the lavas.
Since we can observe its present state, we obtain a rough upper boundary on the thickness of the past atmosphere of Mars for the past 3Gy. This also requires a very small CO_2 concentration in the mantle as higher CO_2 concentrations lead to cases that have no physical explanation. These cases can however be thought of as constraints on the CO_2 contents of the lavas. Thus it seems that CO_2 content can only be less than 200ppm else we still would observe an atmosphere thicker than what is seen at present time. If, on the contrary, there was less CO_2 left three billion years ago (around 30mb typically), our models lead to the conclusion that the present-day atmosphere is much younger (maybe as young as 1 Gy) and has been created essentially by the volcanic degassing occurring in the late period of the planet activity.
It must be noted that when a model with lower volcanic rates is used, such as the one from O'Neill et al. (2007), Earth-like CO_2 concentrations (~500ppm) are viable and yield essentially similar results than what is obtained with low crust production rates. However, in this case, if low CO_2 concentrations are used (typically 100-200ppm), the atmospheric escape becomes the dominant process.
One means to obtain these constraints would be to study the fractionation of isotopes such as $^{14}N/^{15}N$ and $^{12}C/^{13}C$. It would be possible to estimate, independently from the model used here, a rough value for the age of the Martian atmosphere.
It would finally be interesting to model the evolution of the Martian water in the history of Mars as it plays a major role both for habitability and in terms of species formation (the need to have a neutral pH environment for phyllosilicate formation for example).
The main obstacle we encounter for now is our need for a climate model to compute the surface temperature that is required to estimate the state and amount of water on the surface.