MANTLE DEGASSING AND ATMOSPHERIC EVOLUTION: AN APPLICATION TO MARS AND VENUS

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1. Introduction

The atmospheres of Venus and Mars are mainly composed of CO_2, with pressures ranging from 8mbar on Mars to approx. 92 bar on Venus. Presently, it is unknown whether the bulk of atmospheric CO_2 originates from the planetary mantle and is outgassed by volcanoes or whether part of the atmosphere is a residue of primordial gas from accretion. Here, we assume that the entire atmosphere is of internal origin. We calculate if the large difference in pressures observed for these two planets can be explained by the different surface temperatures, sizes and mantle volatile contents, which have a large impact on the mantle viscosity. Furthermore, we investigate how these parameters influence the total amount of outgassed CO_2.

2. Modeling of volcanic outgassing

We estimate the amount of outgassed CO_2 by calculating the amount of melt erupted onto the planetary surface and assuming that a certain amount of CO_2 is outgassed per unit volume of formed crust. To calculate this, we use thermal evolution models and compare the calculated mantle temperature profile at every time-step to the mantle solidus. Here, we assume that intrusive volcanism does not contribute to atmospheric outgassing and set the ratio of extrusive to intrusive volcanism to 15%.

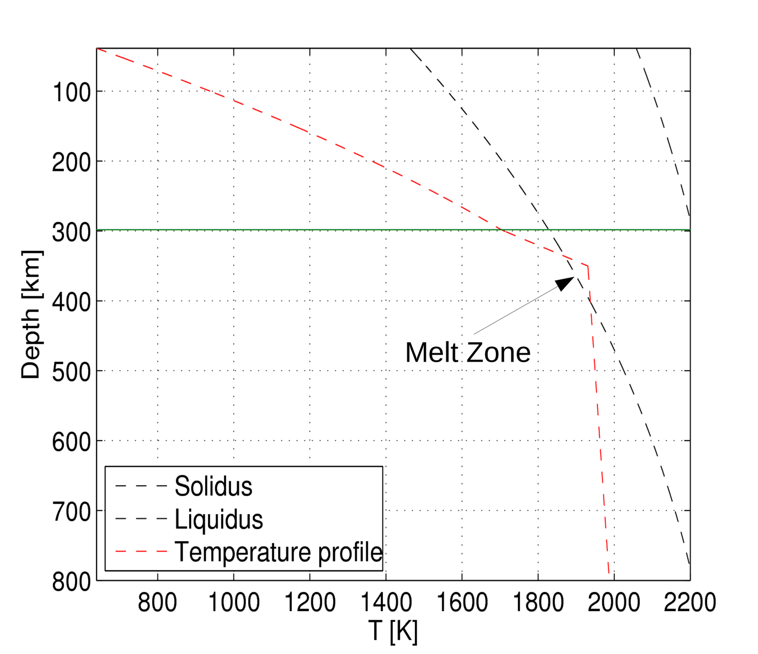


Fig. 1: **Black dashed lines indicate solidus and liquidus of mantle rock. The temperature profile of the planet is indicated by the red dashed line. The green horizontal line shows the depth of the conductive lithosphere.**

The melt zone, from which melt is extracted to the surface, is identified by the black arrow.

In the lithosphere, temperature is calculated by solving the heat conduction equation, whereas the convective mantle is characterized by an adiabatic temperature profile.

The thermal evolution is simulated solving the energy balance equations for lithosphere, mantle and core:

$$\rho_m c_m (T_m - T_l)\frac{D_l}{dt} = -q_m - k_m \left.\frac{\partial T}{\partial r}\right|_{r=R_l} + \rho_{cr} C_{cr}(T_l - T_0)\frac{dD_{cr}}{dt}$$

$$\rho_m c_m \epsilon_m (St+1) V_m \frac{dT_m}{dt} = -q_m A_m - q_l A_m + q_c A_c + Q_m V_m$$

$$\rho_c c_c V_c \epsilon_c \frac{dT_c}{dt} = -q_c A_c$$

Given the amount of melt in the mantle, we can calculate the crustal production rate as well as the total amount of outgassed CO_2.

$$\frac{dV_{cr}}{dt} = \frac{(V_{cr}^m - V_{cr})V_0}{(V_0 - V_{cr}^m)V_{cr}^m} V_a m_a \frac{u}{D_m}$$

$$M_{CO_2} = \int_0^{4.5Gyr} \frac{dV_{cr}}{dt} C_{CO_2} R dt$$

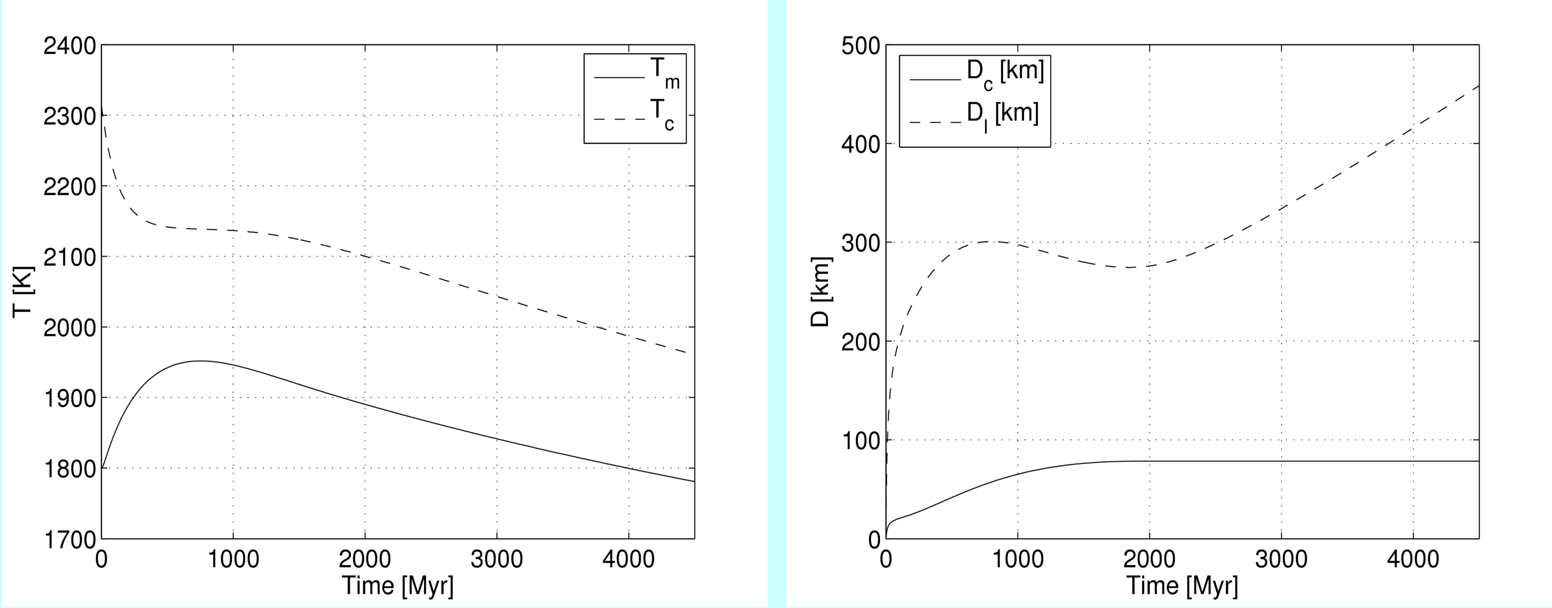
Here, we assume that R=0.15 and C_{CO_2}=514ppm.

Finally, we can calculate the atmospheric pressure:

$$P_{CO_2} = \frac{M_{CO_2} g}{4\pi R_p^2}$$

T	Temperature
r	Radius
$T_{m,c}$	Mantle/core T
$T_{l,0}$	Lithosphere/surface T
$D_{l,cr}$	Lithosphere/crust thickness
R_l	Radius at base of lithosphere
$q_{m,c}$	Mantle/core heat flow
q_l	Heat Piping heat flow
$V_{m,c}$	Mantle/core volume
$c_{m,c}$	Mantle/core heat capacity
$A_{m,c}$	Mantle/core surface area
k_m	Mantle thermal conductivity
Q_m	Mantle heat production rate
$\epsilon_{m,c}$	Ratio upper to average mantle/core T
$\rho_{m,c}$	Mantle/core density
St	Stefan number
V_0	Volume of undepleted mantle
$V_{cr,m}$	Volume of crust/melt zone
m_a	Melt fraction
u	Convection speed scale
D_m	Thickness of convecing layer
R	Ratio extrusive/intrusive volcanism
C_{CO_2}	Concentration of CO_2 in the melt
M_{CO_2}	Mass of CO_2 in the atmosphere
g	Surface acceleration
R_p	Planetary Radius

3. Evolution of the Nominal Model



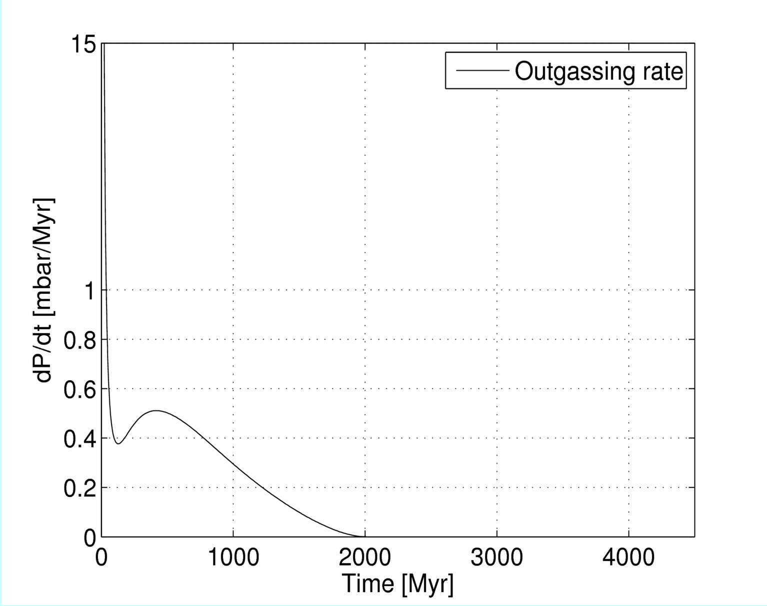


Fig. 2: **Evolution of the mantle temperature T_m and the core temperature T_c (top left), crustal thickness D_c and lithosphere thickness D_l (top right), and outgassing rate (bottom left) for the Mars nominal model (T_m=1800K, $\eta_0=10^{21}$Pas, T_s=220K, R_p=3400km).**

- A primordial crust is formed immediately. This correlates with high outgassing rates in the beginning
- Due to the migration of the melt zone to greater depths with the fast growing lithosphere and the associated increase of pressure, higher temperatures are necessary for melt production resulting in a local minimum in the outgassing rates
- The maximum of T_m induces also a local maximum in the outgassing rate at approximately 500Myr

4. Crustal Erosion

In case the crust gets thicker than the lithosphere, crustal material is recycled into the convecting mantle and crustal thickness is adapted to the lithosphere thickness. This process is supported by an increased vigor of convection (low reference viscosity), high surface temperatures or high initial mantle temperature and promotes volcanic outgassing.

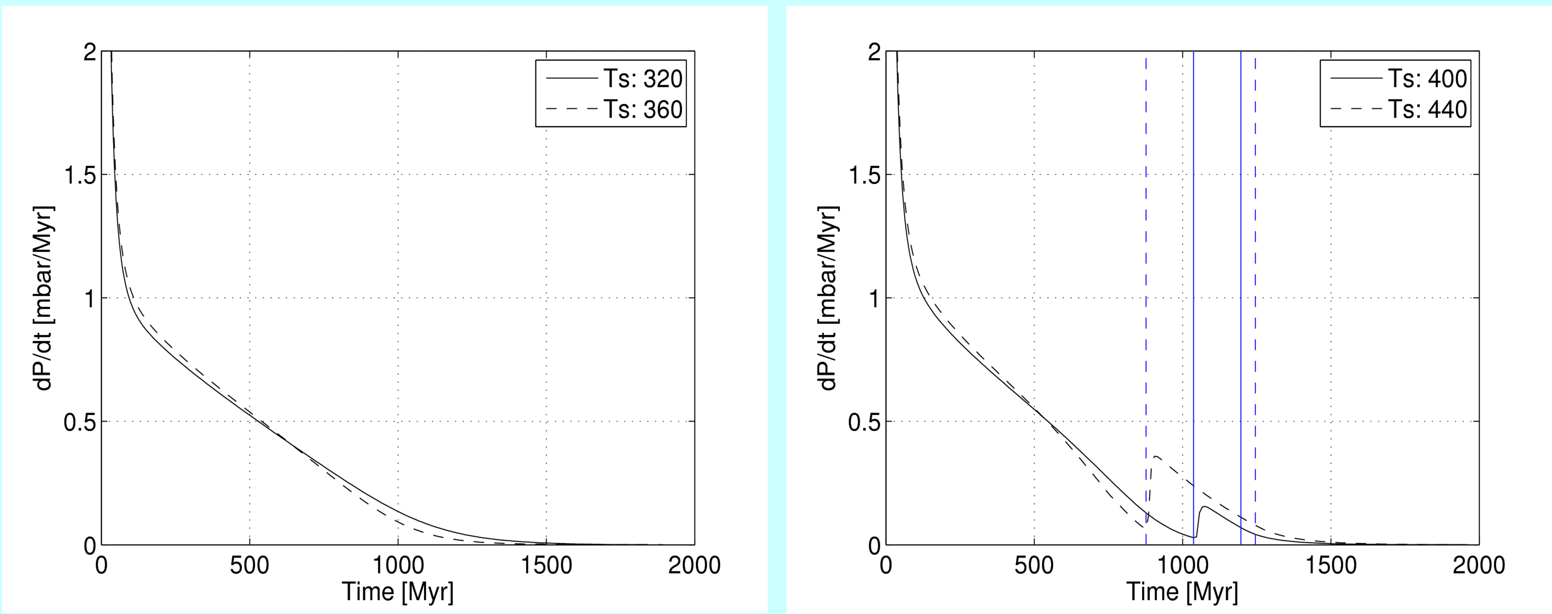


Fig. 3: **Outgassing rates for a Mars-sized planet with $\eta_0=21*10^{19}$Pas and T_m=1800K for different surface temperatures T_s. *Left:* Two cases without crustal erosion. The difference between the two curves is quite small. *Right:* Blue lines indicate start and end of crustal erosion, respectively. By increasing T_s by 40K, the slope of outgassed CO_2 with respect to T_s increases compared to the left case. Crustal erosion results in a strong increase of the outgassing rate.**

5. Volcanic outgassing

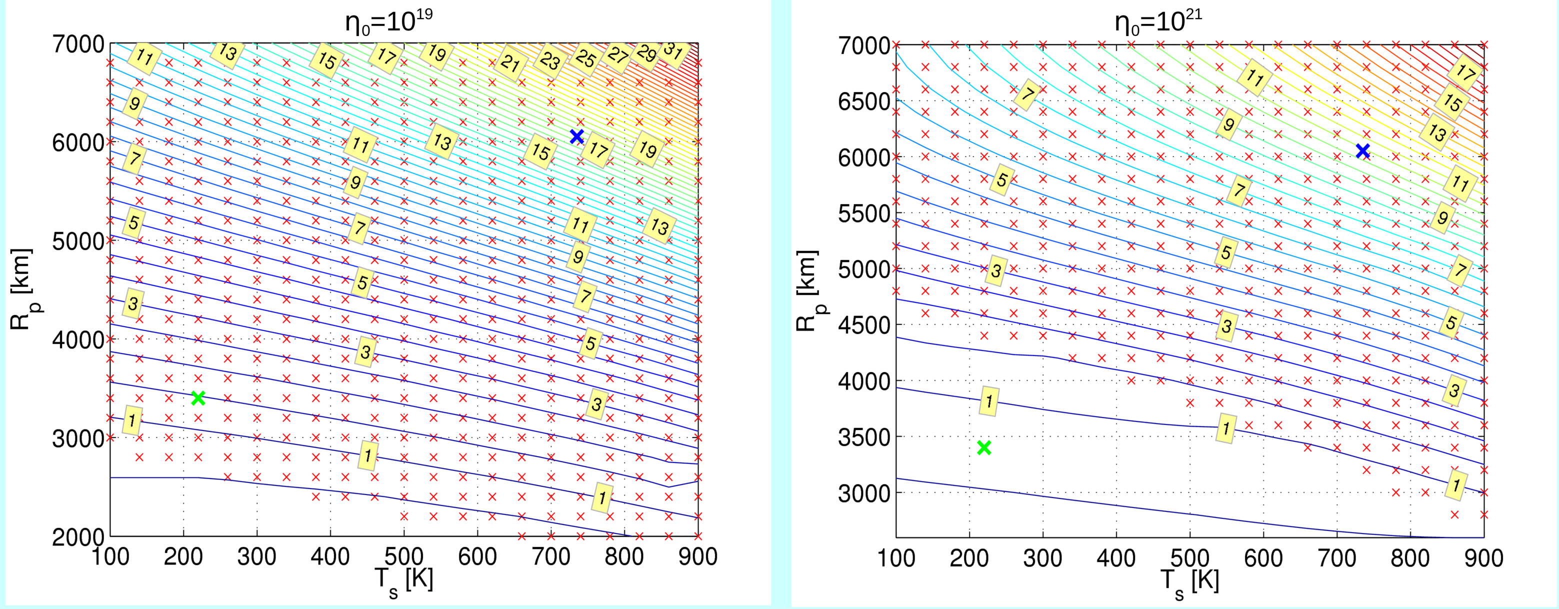


Fig. 4: **Dependence of the outgassed CO_2 partial pressure (in bar) on planetary radius R_p and surface temperature T_s. While varying R_p, the radius of the iron core is uniformly set to the half of R_p. The green crosses indicate the position of Mars and the blue ones that of Venus. Red crosses mark models with crustal erosion. Left: Wet mantle rheology ($\eta_0=10^{19}$ Pas). Right: Dry mantle rheology ($\eta_0=10^{21}$ Pas).**

By comparing the amount of outgassed CO_2 between Mars and Venus varying only the specified parameter, we find that:

- Planetary Radius is the most important parameter and atmospheric pressure increases by a factor of ten from Mars' to Venus' size
- Other parameters like surface temperature and viscosity only double the amount of outgassed CO_2

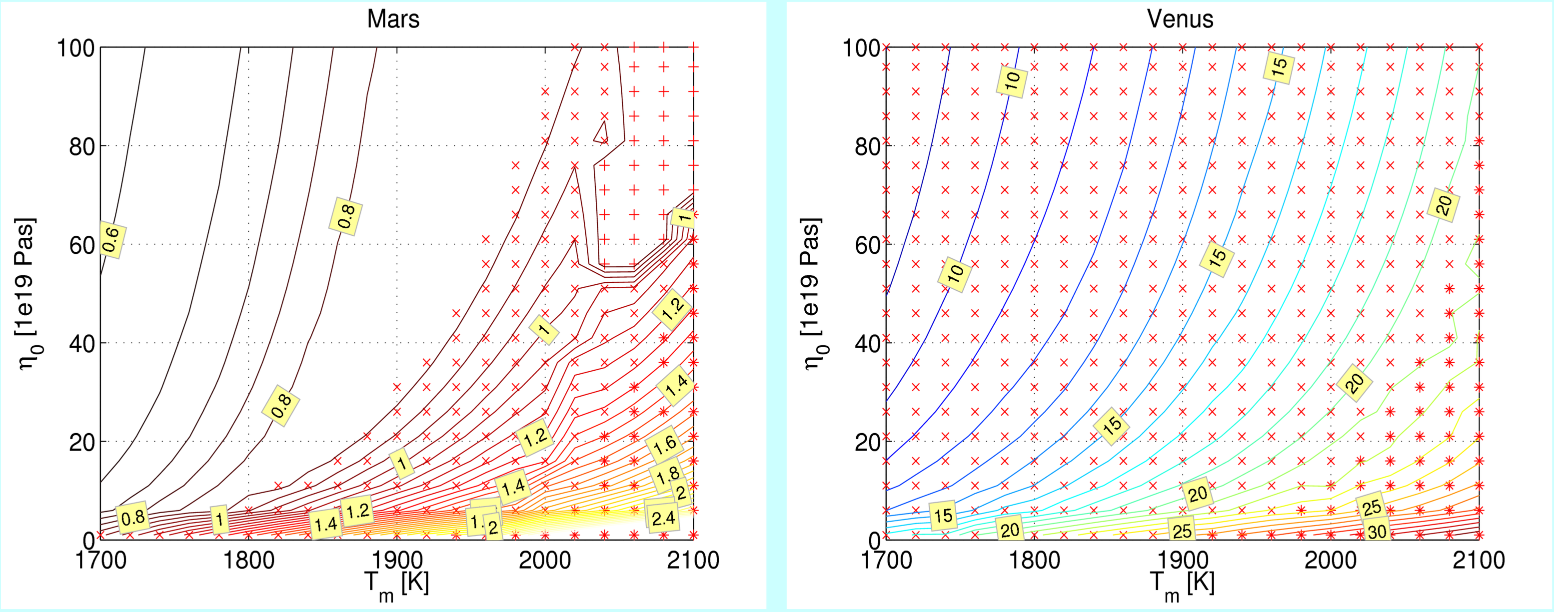


Fig. 5: **Dependence of the outgassed CO_2 partial pressure (in bar) on reference viscosity and initial mantle temperature T_m. Red vertical crosses mark models with crustal erosion. When the maximum crustal thickness was reached (crust enriched with all radioactive elements) during evolution, a red horizontal cross is drawn. Stars are a superposition of the two types of crosses. Left: Mars. Right: Venus.**

6. Conclusions

- With these models, Venus' 92 bar atmosphere cannot be explained by volcanic outgassing and stagnant lid convection.
- However, Venus' larger radius and surface temperature lead up to twenty times higher pressures than for Mars.
- Main uncertainties in the presented models are the assumed mantle CO_2 concentration and the ratio between extrusive to intrusive volcanism.
- Depending on initial mantle temperature and reference viscosity, concentrations of 1300ppm upto 5500ppm are necessary to explain Venus' 92 bar. Values in literature range from 200ppm upto 6000ppm, favoring values around 500ppm.
- Atmospheric erosion is neglected, which will further decrease the today's possible pressure considering volcanic outgassing.
- Atmospheric loss processes must be invoked to explain the thin Martian atmosphere.

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