EPSC Abstracts,
Vol. 4, EPSC2009-616, 2009
European Planetary Science Congress,

Mantle degassing and the origin of the Venusian atmosphere

A. Morschhauser, M. Grott and D. Breuer

German Aerospace Center, Institute of Planetary Research, Berlin, Germany (achim.morschhauser@dlr.de / Tel: +49-30-67055-361 / Fax: +49-30-67055-303)

Abstract

The atmosphere of Venus is mainly composed of CO_2, with a surface partial CO_2 pressure of 87 bar. 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 and outgassed during the formation of the planetary crust. Volcanic outgassing is directly linked to the production of partial melt in the mantle and therefore connected to the planets thermal evolution, which in turn is influenced by the inital mantle temperature after accretion and the mantle volatile content, which has a large impact on mantle viscosity. Here, we investigate if the Venusian atmosphere can be explained by mantle degassing alone assuming that mantle energy transport is in the stagnant lid regime of convection over the entire evolution.

Modelling

In this study, we use one-dimensional thermo-chemical evolution models which are solving the energy conservation equations of the lithosphere, mantle and core [1]. Mantle energy transport is treated using scaling laws for stagnant lid convection. To obtain the amount of outgassed CO_2, we calculate the amount of melt in the mantle by comparing the mantle temperature profile to the mantle solidus at every time-step (Fig.1). The amount of extracted melt building the crust is parametrized with the convection speed scale u and the depletion of the mantle. The crustal production rate is then given by:

$$\frac{dV_{cr}}{dt} = \frac{(V_{cr}^m - V_{cr})V_0}{(V_0 - V_{cr}^m)V_{cr}^m} V_a m_a \frac{u}{D_m} \qquad (1)$$

where V_{cr} denotes the volume of the crust at time t, V_0 the volume of the undepleted mantle, V_{cr}^m the maximum possible volume of the crust (if all radioactive elements are enriched in the crust) and V_a the volume of the melt zone. D_m identifies the radial height of the convecting layer and m_a the melt fraction. Once the crustal production rate has been computed, the amount of outgassed CO_2 is obtained by multiplying the mass of extracted melt with the outgassed CO_2 concentrations χ_{CO_2} at every time-step and integrating over the entire evolution. Although χ_{CO_2} depends on many parameters including melt fraction and the depletion of CO_2 in the mantle, it was assumed for simplicity to be constant. In the presented models, a value of 520 ppm was used as found for terrestrial magmas [2]. Here, we assume that intrusive volcanism does not contribute to atmospheric outgassing and set the ratio of extrusive to intrusive volcanism to 15% [3]. We also consider crustal erosion, which occurs if the crust becomes thicker than the stagnant lid. In this case, we limit the crustal thickness to the lid thickness and recycle the excess crust into the mantle. This process is made feasible by the basalt-eclogite phase transition occuring at 1 GPa.

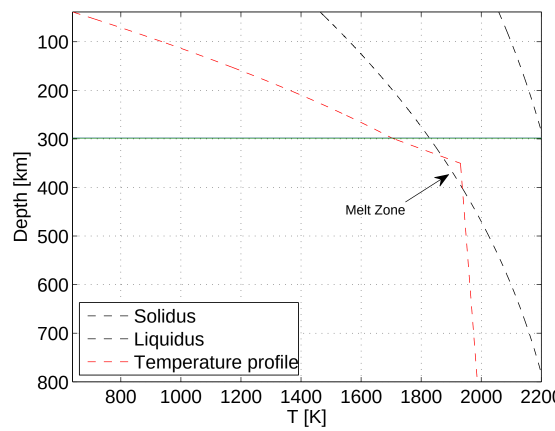

Figure 1: Snapshot of the temperature as a function of depth (red line). Black lines indicate solidus and liquidus of mantle rock. The temperature profile of the planet is indicated by the red line. The green line shows the base of the conductive lithosphere. The melt zone is identified by the black arrow. In the lithosphere, temperature is calculated by solving the heat conduction equation, whereas the convective mantle is characterized by an adiabatic temperature profile.

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Results

We have investigated the dependence of the amount of outgassed CO_2 on mantle volatile content (η_0) and initial mantle temperature T_m for Venus.

In Fig.2, the dependence of the outgassed CO_2 partial pressure P_{CO_2} (in bar) on the reference viscosity η_0 and the initial mantle temperature T_m is shown for Venus. As the amount of volatiles present in the mantle significantly influences the mantle viscosity and already small amounts of water can lower the viscosity by orders of magnitude, the vigor of mantle convection increases for models with larger volatile content, resulting in larger amounts of crustal production and therefore outgassing. For a dry mantle rheology, pressures range from P_{CO_2} equal to 8 bar upto 20 bar, whereas for a wet mantle rheology, we obtain pressures between 17 bar and 34 bar, depending on the initial mantle temperature. Increasing the initial mantle temperature leads to higher P_{CO_2} as more melt will be available to outgas CO_2.

Furthermore, we find that crustal erosion is an important process supporting volcanic outgassing. If the crust is eroded, the melt zone will be moved to shallower depth where lower temperatures are necessary to produce partial melt. Besides, the mantle will be refertilized as crustal material is eroded and resubducted into the mantle. This increases the crust production rate and therefore the amount of outgassed CO_2.

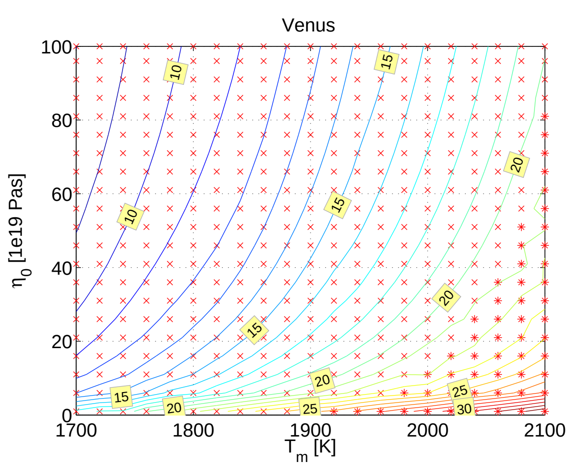

Figure 2: Outgassed CO_2 partial pressure P_{CO_2} (in bar) as a function of reference viscosity η_0 and initial mantle temperature T_m. Red vertical crosses mark models with crustal erosion. When the maximum crustal thickness was reached additionally to crustal erosion during evolution, a red star is drawn.

Discussion

We calculated the amount of outgassed CO_2 depending on the reference mantle viscosity η_0 and initial mantle temperature T_m for Venus for a large parameter range. As these are the main parameters influencing mantle partial melt production, Venus' 87 bar CO_2 atmosphere cannot be explained by volcanic outgassing and stagnant lid convection using the introduced model and CO_2 concentrations of 520 ppm.

To explain Venus' thick atmosphere, other mechanisms must be considered. Global resurfacing events as suggsested for Venus provide one such mechanism. According to [4], eight resurfacing events are required to explain Venus' atmosphere. Another explanation might be that part of the atmosphere is a remnant of the primordial one.

Furthermore, main uncertainties in the presented model are the assumed mantle CO_2 concentration χ_{CO_2} and the ratio of extrusive to intrusive volcanism. Values in literature range from 200 ppm upto 6000 ppm, favoring the values around 500 ppm to 2000 ppm and 6000 ppm being rather unrealistic [5]. Treating χ_{CO_2} as a variable, concentrations of 1500 ppm upto 5500 ppm are necessary to explain the 87 bar CO_2 partial pressure on Venus. Therefore, only a small section of the parameter range is able to outgas enough CO_2 assuming reasonable values for χ_{CO_2}.

However, by taking atmospheric escape processes into account, which we have neglected in this study, even more outgassed CO_2 is necessary to explain today's atmospheric pressure. These processes as well as a more detailed model of CO_2 concentrations treating χ_{CO_2} as a function of CO_2 depletion of the mantle will be investigated in future work.

Summarizing, it seems hardly possible for Venus' atmosphere to be of internal origin as only very high values of χ_{CO_2} are compatible with this assumption.

References

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