EPSC Abstracts
Vol. 13, EPSC-DPS2019-2004-2, 2019
EPSC-DPS Joint Meeting 2019

EPSC
EPSC-DPS Joint Meeting 2019
15–20 September 2019 | Geneva, Switzerland

Venus' atmosphere - insights from interior models

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Abstract

Most of Venus' history is hidden from us, since its surface is covered by relatively young material. Different mechanisms have been suggested in the literature to explain why Venus evolved in such a different way than Earth - including models that link the planetary interior to the evolving atmosphere. It is still not clear how ancient Venus' present-day atmosphere is, and if its composition and mass was set already during the earliest stages of planet accretion and magma ocean degassing, if it changed substantially over time, or if the planet could have had at least for some time much more hospitable surface conditions than today. To answer these questions, different disciplines need to work together to combine insights from geological observations, geochemical and atmosphere chemistry studies, and interior modeling and degassing.

1. Model

To address different alternative outgassing scenarios, I developed a coupled model to study the interior composition and structure of rocky planets [1]. Thermodynamic and transport properties of the rocky mantle are determined based on the assumed mineralogy [2, 3]. With this model, it is possible to reconstruct the thermal evolution of the mantle, and predict from that the amount of volcanic activity and degassing over time [2, 4, 5], depending on the volatile concentrations, partitioning behaviour and redox conditions in the mantle [6, 7]. The code was recently coupled to a gas speciation model in the melt [8] to allow for outgassing of reduced (e.g., H_2, CO) and oxidized species (e.g., H_2O, CO_2) depending on the melt chemistry.

2. Coupled interior-surface models

The first model coupling the atmosphere to the interior used a 1D parameterized model of the interior of Venus [9] and suggested that the feedback between atmosphere and interior leads to strong enhancement in melting efficiency, leading to more volcanic outgassing over time than for an uncoupled model.

[4] used 2D and 3D mantle models to investigate not only the temperature and melt evolution of the mantle, but also possible mobilization of the surface, to explain the young, average surface age. We could show that under the hot mantle conditions that Venus most likely experiences, gradual resurfacing due to melt extraction and convective crust mobilization (operating at very high surface temperatures, i.e. after large amounts of H_2O have been released into the atmosphere) can lead to in general young surface ages, and will continue to reshape its surface, see Fig. 1, with gradually decreasing strength.

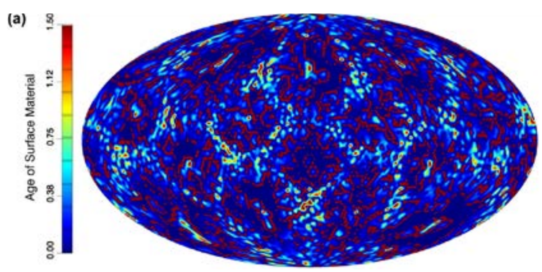

Figure 1: Example simulation result for Venus after 4.5 Gyr of evolution, showing the resulting surface ages in Gyr due to crustal mobilization and melting (from [4]).

Using a similar approach with a different atmosphere model, [10] could show that in times that Venus' atmosphere did not contain large amounts of water vapor, hence at cooler surface conditions, stress patterns can occur leading to brittle deformation and subduction-like resurfacing, also explaining the young average surface of Venus. Other explanations have been suggested in the literature to explain Venus' young surface, such as crustal delamination or episodic resurfacing. The models mentioned above assumed that Venus' surface was not too different in its past compared to today, whereas other studies investigate the possibility of a once Earth-like, cool and possibly even water-rich surface (e.g., [11]).

3. Venus' primary and secondary outgassed atmosphere

The big question remains, if Venus did start under the same conditions as Earth, or if the orbit closer to the sun would have decided Venus' fate. [12] suggested that for a primary outgassed water steam atmosphere, the duration of the magma ocean could have lasted up to 100 Myrs, leading to a desiccated interior.

It is not clear, though, what the composition of the primary outgassed atmosphere due to magma ocean solidification was, and if some of the primary atmosphere accreted from the solar nebula mixed with it. In magma ocean degassing scenarios (e.g. [13, 14]), it is often assumed that the main volatiles expelled from the magma would be CO_2 and H_2O, similar to what we observe today in Earth's oxidized volcanic gases. However, during the magma ocean, if an iron core formed (as it definitely did for Earth and Mars, and most likely also for Venus), the magma ocean would have operated under a much more reduced state [15], and at least the first degassing products would rather have been reduced gases such as H_2 and CO, which (at least in the case of hydrogen) would be eroded to space very quickly. On the other hand, the variety of chemical species that can be released by secondary outgassing on Venus is strongly limited by the high present-day atmospheric pressure, leading to mostly outgassing of CO and CO_2, since other species such as water and sulfur-containing gases, if they are abundant in the mantle and partition into the melt, may stay dissolved in the magma [16]. Venus' present-day dry atmosphere can therefore be explained by several different factors.

Acknowledgements

Part of this work has been performed under the HPC-EUROPA2 project (Project No. 228398) with the support of the European Commission – Capacities Area – Research Infrastructures. In addition, it was supported by the Helmholtz Association through the Planetary Evolution and Life research alliance.

The authors further acknowledge support by the German Research Foundation (DFG) within the SFB-TRR 170 “Late Accretion onto Terrestrial Planets” (subprojects C5 and C6).

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